UNIVERSITY
OF OSLO

High-resolution beamforming in ultrasound imaging

Sverre Holm

MEDT8007 Simulation Methods in Ultrasound Imaging - NTNU

Sverre Holm

Journal Publications

- J.-F. Synnevåg, A. Austeng, and S. Holm, "Adaptive beamforming applied to medical ultrasound imaging," IEEE UFFC (Special issue on high resolution ultrasonic imaging), Aug. 2007
- J.-F. Synnevåg, A. Austeng, and S. Holm, ”Benefits of High-Resolution Beamforming in Medical Ultrasound Imaging”, IEEE UFFC, Sept. 2009.
- J.-F. Synnevåg, A. Austeng, and S. Holm, A Low Complexity Data-Dependent BeamformerIEEE UFFC, Feb. 2011.
- C.-I. C. Nilsen & I. Hafizovic, Beamspace Adaptive Beamforming for Ultrasound Imaging, IEEE UFFC, Oct. 2009.
- C.-I. C. Nilsen & S. Holm, Wiener Beamforming for Ultrasound Imaging, IEEE UFFC, June 2010

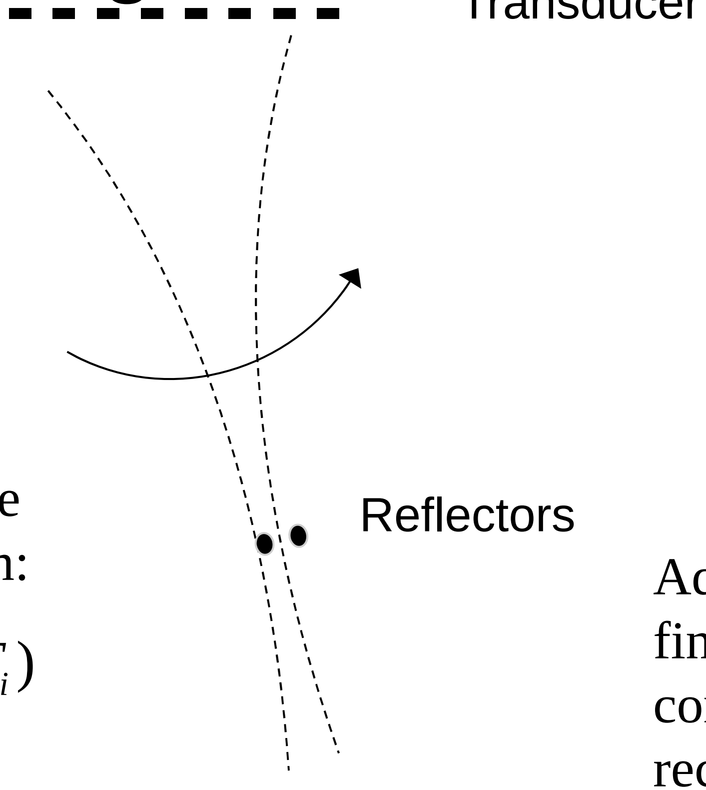
Conference Presentations

- J. Synnevåg, A. Austeng, and S. Holm, "Minimum Variance Adaptive Beamforming Applied To Medical Ultrasound Imaging," in Proc IEEE Ultrasonics Symposium, Rotterdam, Netherlands, 2005.
- J.-F. Synnevåg, A. Austeng, and S. Holm, "High frame-rate and high resolution medical imaging using adaptive beamforming," in Proc. IEEE Ultrasonics Symposium, Vancouver Canada, Oct 2006.
- J.-F. Synnevåg, C. I. Nielsen, and S. Holm, "Speckle Statistics in Adaptive Beamforming", IEEE Ultrasonics Symp., NY, Oct. 2007
- A. Austeng, T. Bjastad, J.-F. Synnevaag, S.-E. Masoy, H. Torp and S. Holm "Sensitivity of Minimum Variance Beamforming to Tissue Aberrations", IEEE Ultrasonics Symposium, Nov. 2008.
- J.-F. Synnevåg, S. Holm and A. Austeng, "Low-Complexity Data-Dependent Beamforming", IEEE Ultrasonics Symposium, Nov. 2008.
- K. Holfort, A. Austeng. J.-F. Synnevåg, S. Holm, F. Gran, J. A. Jensen, "Adaptive Receive and Transmit Apodization for Synthetic Aperture Ultrasound Imaging," in Proc. IEEE Ultrasonics Symposium, Rome, Italy, Sept. 2009.
- A. Austeng, A. F. C. Jensen, J.-F. Synnevåg, C.-I. C. Nilsen, S. Holm, "Image Amplitude Estimation with the Minimum Variance Beamformer," in Proc. IEEE Ultrasonics Symposium, Rome, Italy, 2009.
- A. E. A. Blomberg, I. K. Holfort, A. Austeng, J.-F. Synnevåg, S. Holm, J. A. Jensen, "APES Beamforming Applied to Medical Ultrasound Imaging" in Proc. IEEE Ultrasonics Symposium, Rome, Italy, Sept. 2009.

Sonar:

- A. E. A. Blomberg, A. Austeng, R.E. Hansen, S. Holm, "Minimum Variance Adaptive Beamforming Applied to a Circular Sonar Array," Underwater Acoustic Measurements: Technologies & Results, Greece, June 2009.
- S. Jetlund, A. Austeng, R.E. Hansen, S. Holm, "Minimum variance adaptive beamforming in active sonar imaging," Underwater Acoustic Measurements: Technologies & Results, Greece, June 2009.

Beamforming



Delay-and-Sum, DAS:
Pre-determined aperture shading, delay, and sum:

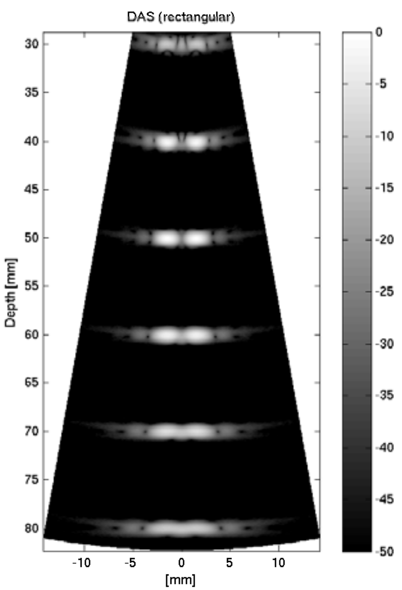
$$A(t) = \sum_{k=1}^{M} w_i x_i (t - T_i)$$

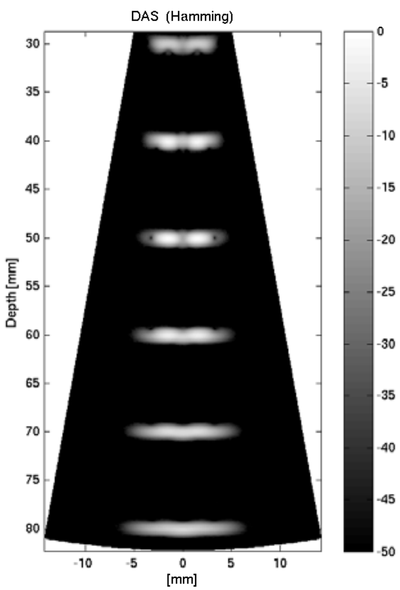
w_i: typ. rectangular or Hamming
(real, symmetric)

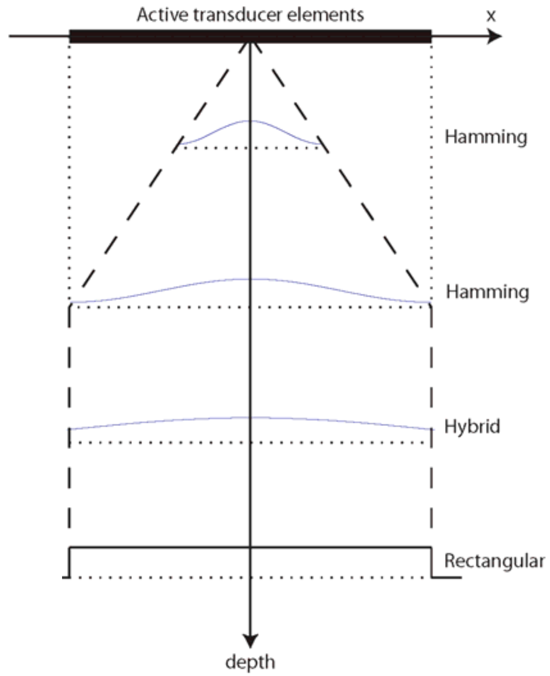
Adaptive beamformers find w_i from spatial correlations in the recorded data, i.e. they adapt to the data

Data is used twice!

Rectangular or Hamming?

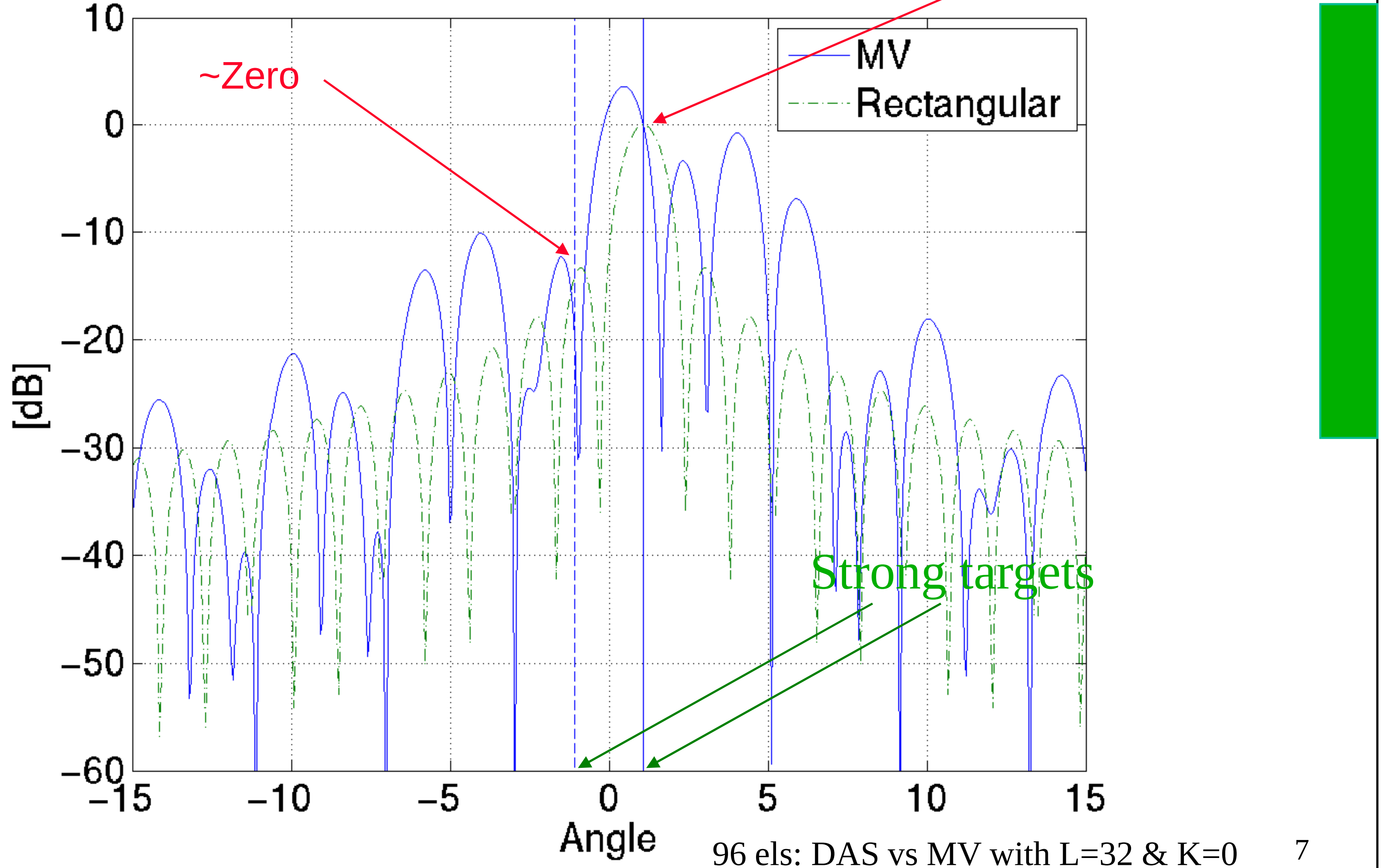






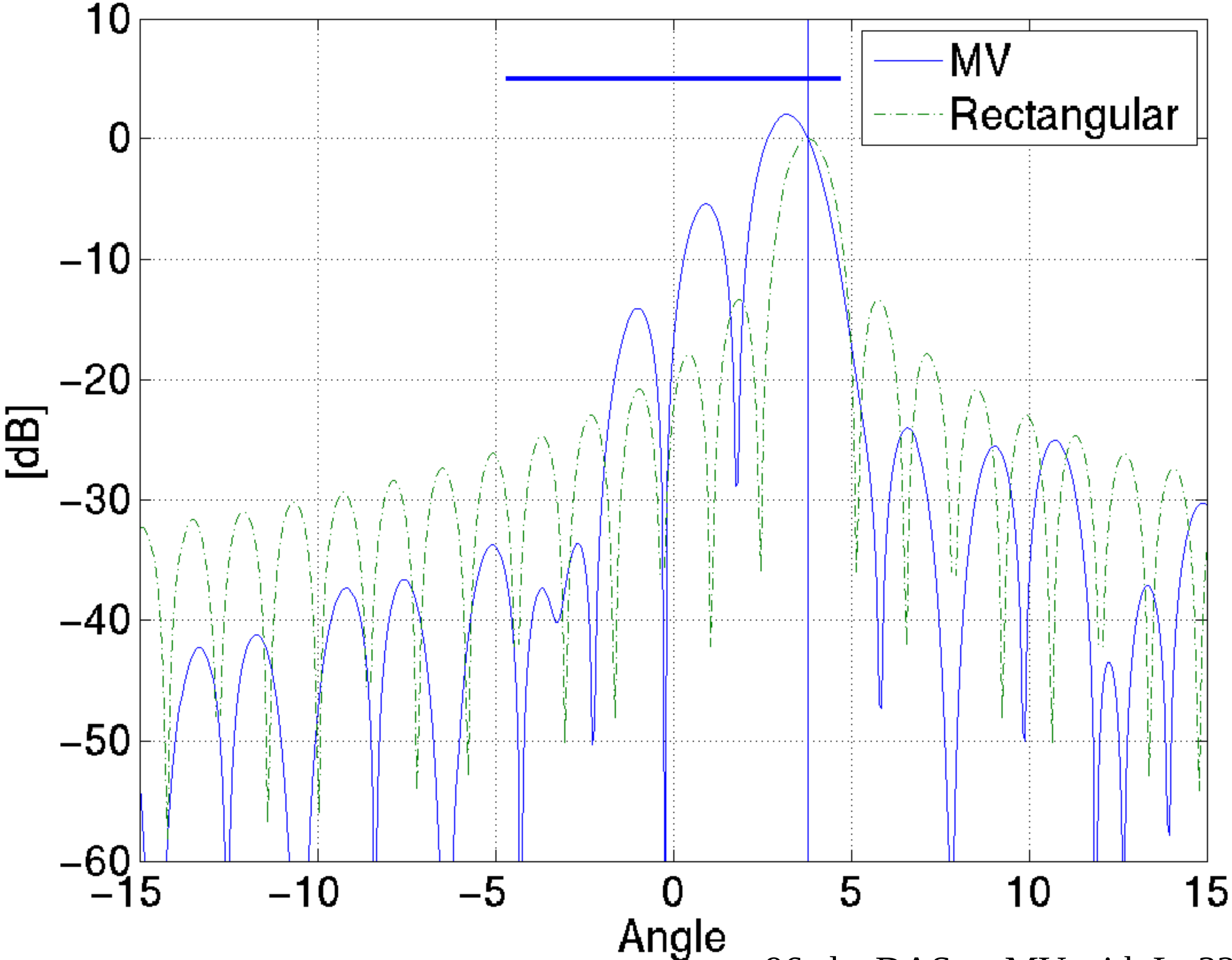
UNIVERSITY OF OSLO

Examples of beampatterns (two wiretargets, 80 mm)



96 els: DAS vs MV with L=32 & K=0

Beampatterns (cyst)



96 els: DAS vs MV with L=32 & K=0

Origins

- *J. Capon,“High-resolution frequency-wavenumber spectrum analysis,” Proc. IEEE*, pp. 1408–1418, 1969.
- Finn Bryn, ”*Optimum Signal Processing of Three-Dimensional Arrays Operating on Gaussian Signals and Noise*,” Journ. Acoust. Soc. Am., pp. 289-297, 1962.

Terminology

- High resolution beamforming
- Minimum variance beamforming
- Capon beamforming
- Adaptive beamforming
  - But not phase aberration correction

Beamforming: Matrix formulation

- Single-frequency output of beamformer:
  y = w'x, where w has phase
- Power: P_{yy} = yy' = w'x(w'x)'=w'xx'w=w'R_{xx}w
- Signal, x $\propto$ e, steering vector
- Broadband: sum over all frequencies
  $\Leftrightarrow$ delay-and-sum beamformer:

$$y(t) = \sum_{m=0}^{M-1} w_m y_m(t - \Delta_m)$$

Steering vector

- Signal, x $\propto$ e, steering vector

$$e = \begin{bmatrix} exp(-j \cdot \vec{k}_0^0 \cdot \vec{x}_0) \\ \vdots \\ exp(-j \cdot \vec{k}_{M-1}^0 \cdot \vec{x}_{M-1}) \end{bmatrix}$$

- Plane wave: $\vec{k}_m^0 = \vec{k}^0 = \frac{2\pi}{\lambda}\vec{\zeta}$
- Uniform Linear Array: $\vec{x}_m = m \cdot d \cdot \vec{i}_x$
- Plane wave on ULA:

$$exp(-j \cdot \vec{k}_m^0 \cdot \vec{x}_m) = exp(-j\frac{2\pi}{\lambda} m \cdot d \cdot \vec{\zeta}\vec{i}_x) = exp(-j\frac{2\pi \cdot m \cdot d}{\lambda}\sin\phi)$$

Minimum variance beamforming

- Minimize output power: $$\min_{\mathbf{w}} \mathbf{w}^{\mathbf{H}} \mathbf{R} \mathbf{w}$$
- subject to unity gain in desired direction: $$\mathbf{w}^{\mathbf{H}} \mathbf{a} = 1$$
- Because of pre-steering and pre-focusing (straight ahead): $$\mathbf{a} = \bar{\mathbf{1}}$$

Minimum variance

- Weight:

$$w = \frac{R^{-1}e}{e^{H}R^{-1}e}$$

- Complex weights vary with covariance matrix, i.e. the data and direction (in e)
- Results in adaptive suppression in the direction of the largest interferers
- Result: $P_{MV} = w' R_{xx} w = 1/(e^{H} * R^{-1} * e)$

Minimum variance beamforming

- In practice **R** is replaced by the sample covariance matrix
  - Only a few time-samples are available
- Averaging in space and time
  - Subaperture averaging
    - » J. E. Evans, J. R. Johnson, and D. F. Sun, “High resolution angular spectrum estimation techniques for terrain scattering analysis and angle of arrival estimation,” Proc. 1st ASSP Workshop Spectral Estimation, Hamilton, Ont., Canada, pp. 134–139, 1981.
  - Diagonal loading: R is replaced by $R + \delta \cdot \mathrm{tr}\{R\} \cdot I$
    - » J. Li, P. Stoica, and Z. Wang, “On robust Capon beamforming and diagonal loading,” *IEEE Trans. Signal Processing*, vol. 51, no. 7, pp. 1702–1715, July 2003.

The Effect of Signal Coherence

- 2 sources in two different directions (Synnevaag 2009, PhD):

$$\mathbf{X}(t) = s_0(t) \cdot \mathbf{a}(k_0) + s_1(t) \cdot \mathbf{a}(k_1) \tag{24}$$

The output of a beamformer operating on these measurements is:

$$\begin{aligned} z(t) &= \mathbf{w}^H \mathbf{X}(t) && (25) \\ &= s_0(t)\mathbf{w}^H \mathbf{a}(k_0) + s_1(t)\mathbf{w}^H \mathbf{a}(k_1) && (26) \\ &= W(k_0)s_0(t) + W(k_1)s_1(t) && (27) \\ &= s_0(t) + W(k_1)s_1(t) && (28) \end{aligned}$$

As we steer towards s_0, the constraint in (22) forces $W(k_0) = 1$. The variance of $z(t)$ becomes:

$$\begin{aligned} E\{|z(t)|^2\} &= E\left\{|s_0(t) + W(k_1)s_1(t)|^2\right\} && (29) \\ &= E\left\{|s_0(t)|^2\right\} + 2\mathrm{Re}\left\{E\left\{s_0(t)s_1^*(t)\right\}\right\} + W(k)^2 E\left\{|s_1(t)|^2\right\}, && (30) \end{aligned}$$

The Effect of Signal Coherence

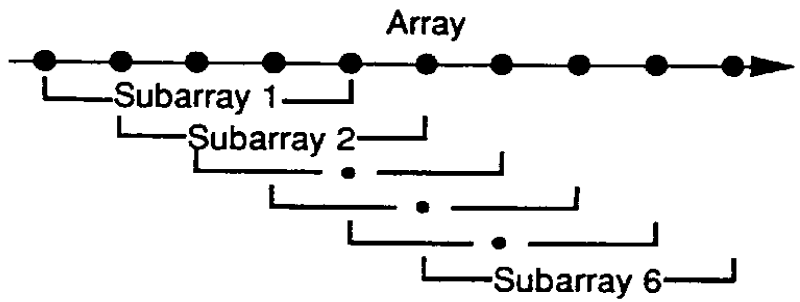
- Output is critically dependent on correlation between sources:

$$\begin{aligned} E\{|z(t)|^2\} &= E\left\{|s_0(t) + W(k_1)s_1(t)|^2\right\} && (29) \\ &= E\left\{|s_0(t)|^2\right\} + 2\mathrm{Re}\left\{E\left\{s_0(t)s_1^*(t)\right\}\right\} + W(k)^2 E\left\{|s_1(t)|^2\right\}, && (30) \end{aligned}$$

where $\mathrm{Re}\{\cdot\}$ denotes the real part. To minimize interference, the MV solution should form a null in the direction of s_1, *i.e.* $W(k_1) = 0$. The variance of the output of the beamformer in (30) would then be equal to the variance of $s_0(t)$. However, we see that if $s_0(t)$ and $s_1(t)$ are correlated, the second term in (30) may be non-zero and negative. Hence, there may exist a solution in which the variance is smaller than $E\{|s_0(t)|^2\}$. ***E.g.*** if $E\{|s_0(t)|^2\}$, $E\{|s_1(t)|^2\}$ and the cross-correlation between s_0(t) and $s_1(t)$ is equal to one, the variance of $z(t)$ becomes zero if $W(k_1) = -1$. The MV beamformer will favour $W(k_1) = -1$ over $W(k_1) = 0$, as the output of the beamformer has a smaller variance. In this situation signal cancellation has occurred.

Coherent signals and spatial smoothing

- Spatial smoothing is the cure against signal cancellation
  - Averaging over linear aperture
  - Forward-backward averaging



- Compromise between
  - … smoothing to avoid the effect of coherent signals
  - … and loss of resolution due to subaperture smaller than physical aperture

7.3.4

Robustness

- The more ”tuned” an algorithm is, the more sensitive it is to deviations from assumptions
- Assumed form of the signal vector implies perfect knowledge of:
  - Sensor positions
  - Sensor gains
  - Sensor phase
    - changes if speed of propagation in medium is incorrect
  - Cross coupling

Robust Constrained Optimization

- Minimum variance beamforming:
  1. Minimize **w'Rw** with respect to **w**
  2. Subject to **e'w** = 1 – unity gain, desired direction
- Robustness criterion 1:
  2. Subject to **(e+δ)'w** = 1 and $|\delta|^2 \leq \varepsilon^2$
     - » δ represents errors in signal vector
- Robustness criterion 2:
  2. Subject to **e'w** = 1 and $|w|^2 \leq \beta^2$
     - ≈ β represents a limit on the weight vector's norm
     - » Not directly related to robustness, but …

7.4.3

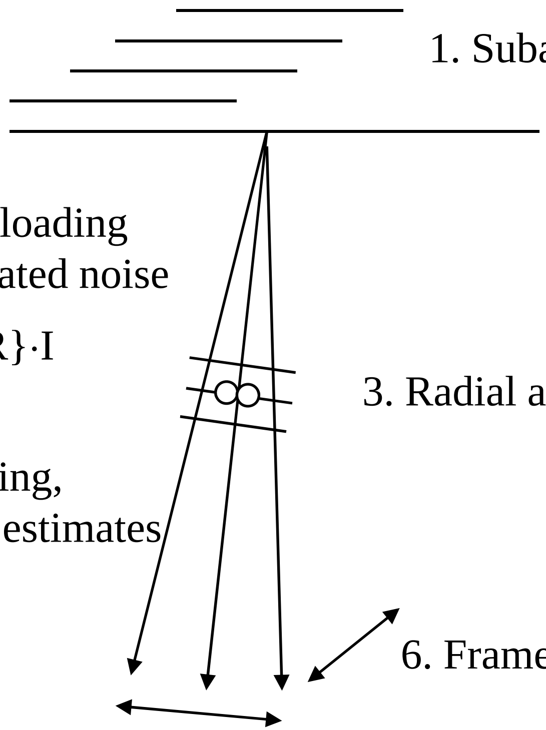
Robust Constrained Optimization

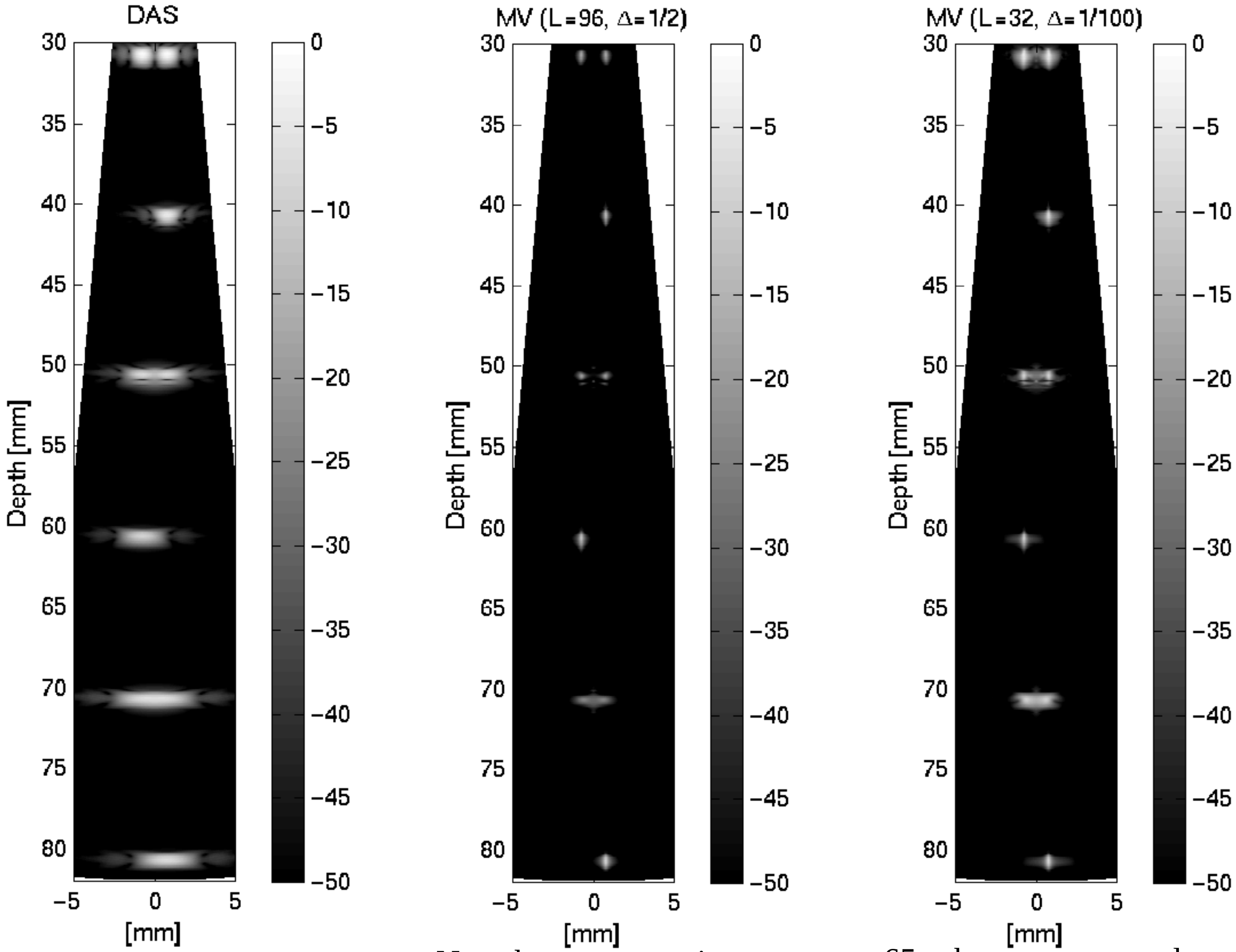
- Both cases $\Rightarrow$ add a scaled identity matrix to covariance estimate: $\mathbf{R} \rightarrow \mathbf{R} + \varepsilon\, \mathbf{I}$
  - $\Leftrightarrow$ Regularization in linear algebra
  - $\Leftrightarrow$ Diagonal loading in array processing
- Value of ε depends on criterion and is signal dependent
  - Du, Yardibi, Li, Stoica, Review of user parameter-free robust adaptive beamforming algorithms, Digital Signal Processing, 2009
- Simple solution used by us:
  - $\varepsilon = \delta \cdot$ {avg pwr} $= \delta \cdot \mathrm{tr}\{R\}/L$, where L= sub. ap length

Adaptation to Medical Ultrasound

- Focused System
  - Pre-beamforming of receiver: steering and focusing
  - Adaptive beamformer only applies complex weights to model deviations
- Transmitter beam
  - Unfocused or focused beam like in medical scanners
  - Single beam, ~omnidirectional:
  - Plane wave as in acoustic streaming imaging
- From Passive to Active System
  - Coherence
  - Target cancellation
  - Illustrated in next plots

Smoothing and conditioning





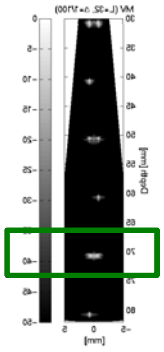
Spacing: 1.5 mm

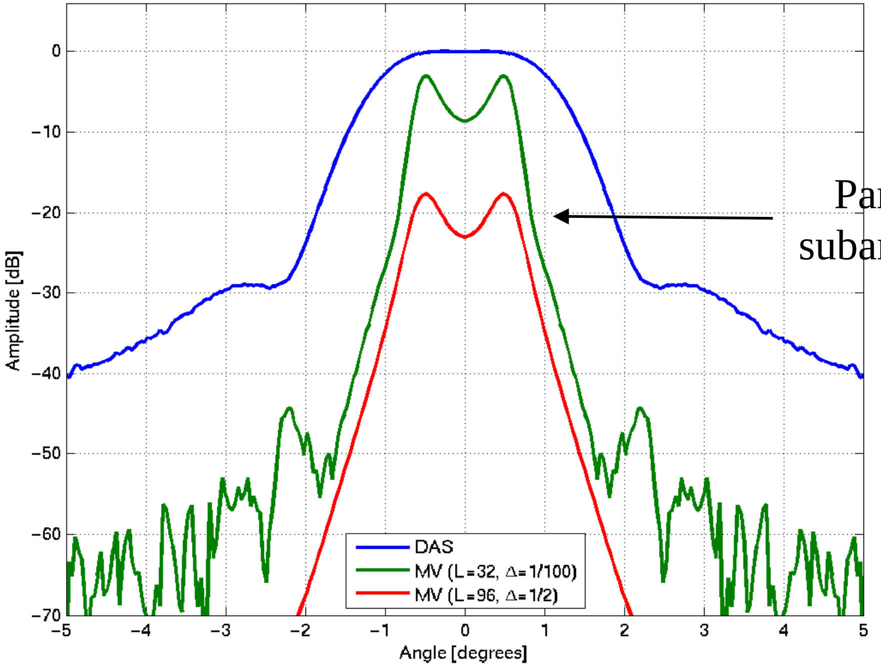
No subarray averaging,
Heavy diagonal loading,
else single points also suffer

65 subarrays averaged,
Light diagonal loading

UNIVERSITY
OF OSLO

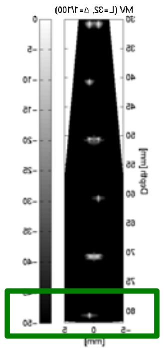
Two targets, unresolvable by DAS

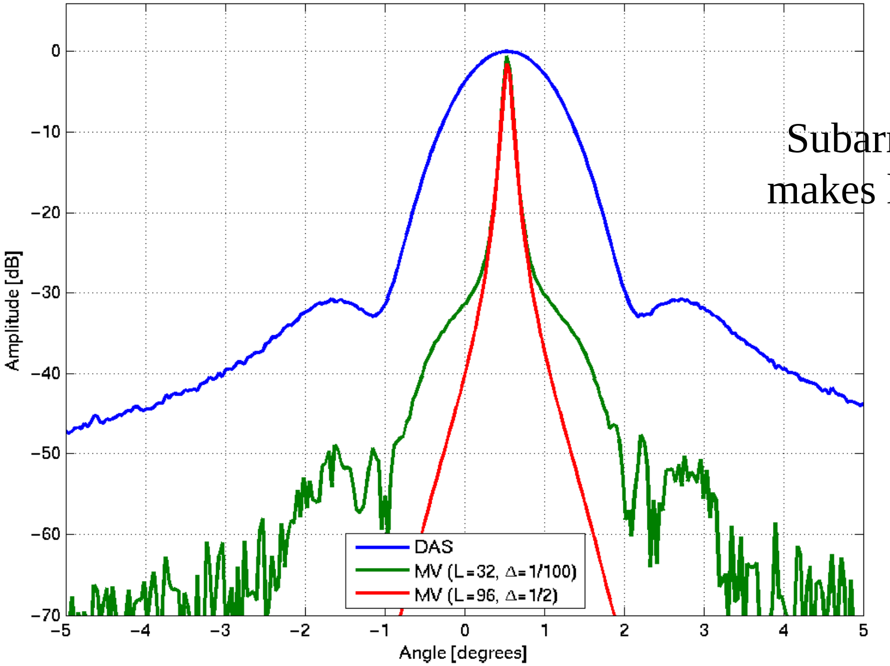




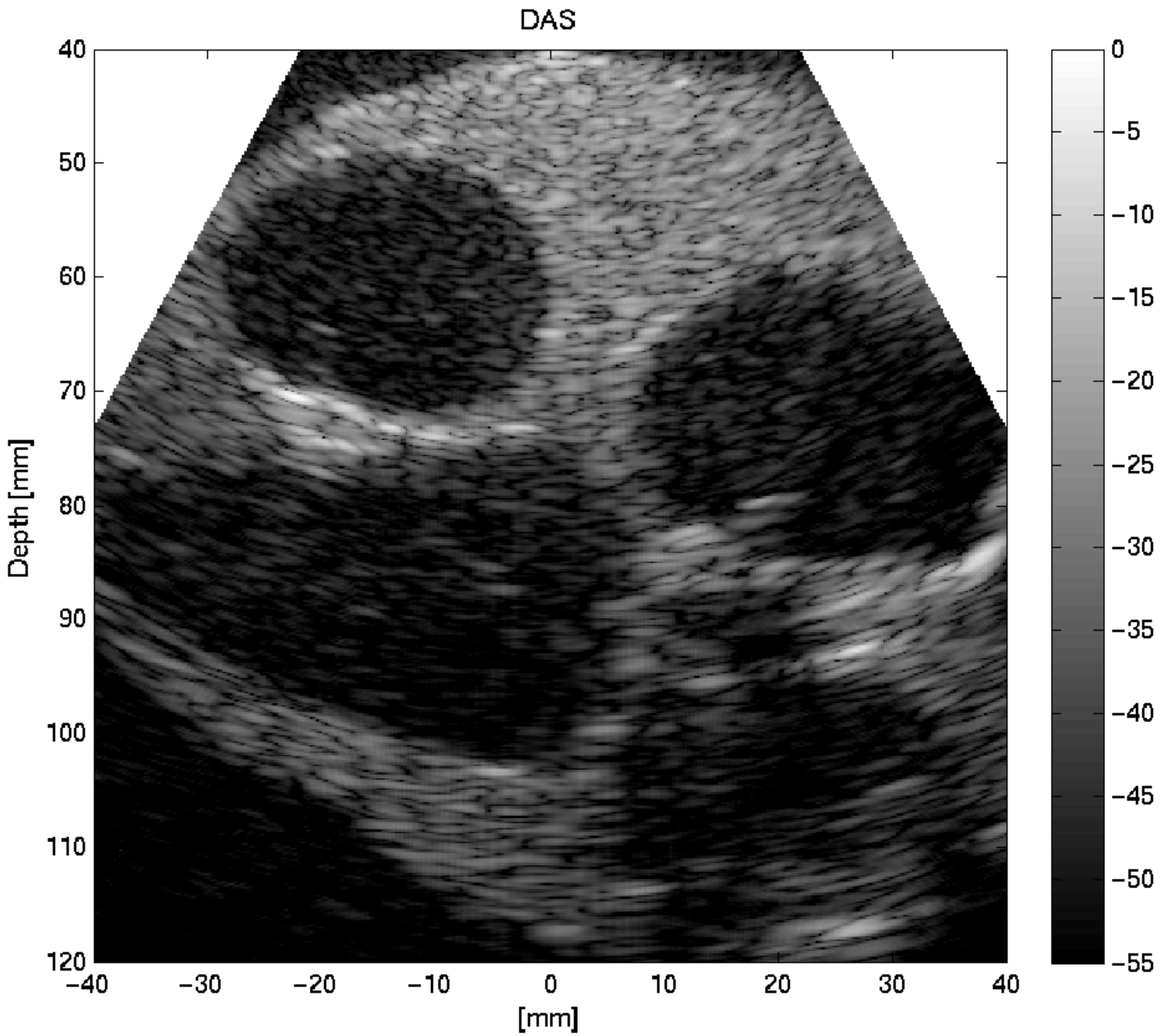
Partial cancellation without subarray averaging; ~15 dB loss

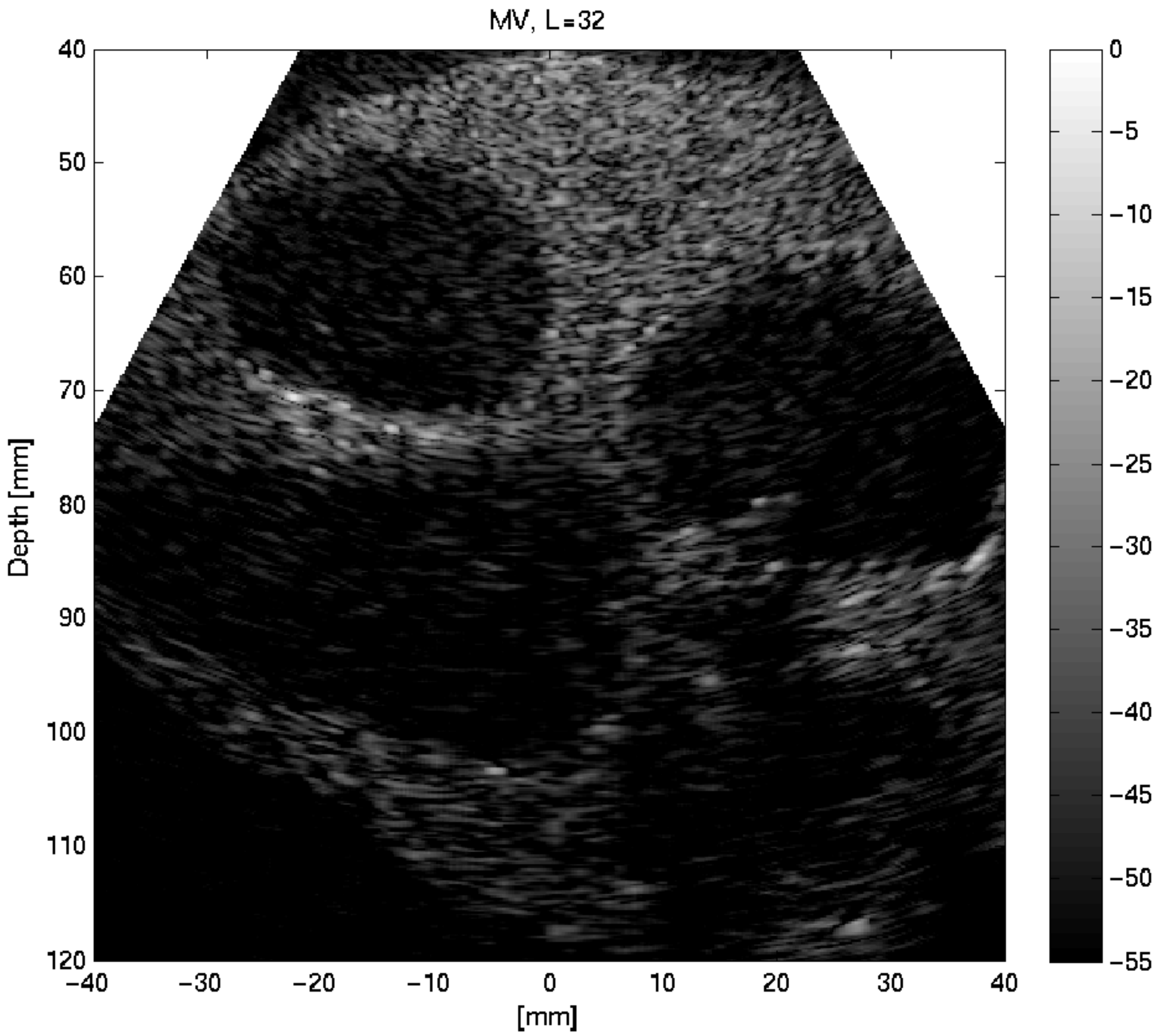
Single target



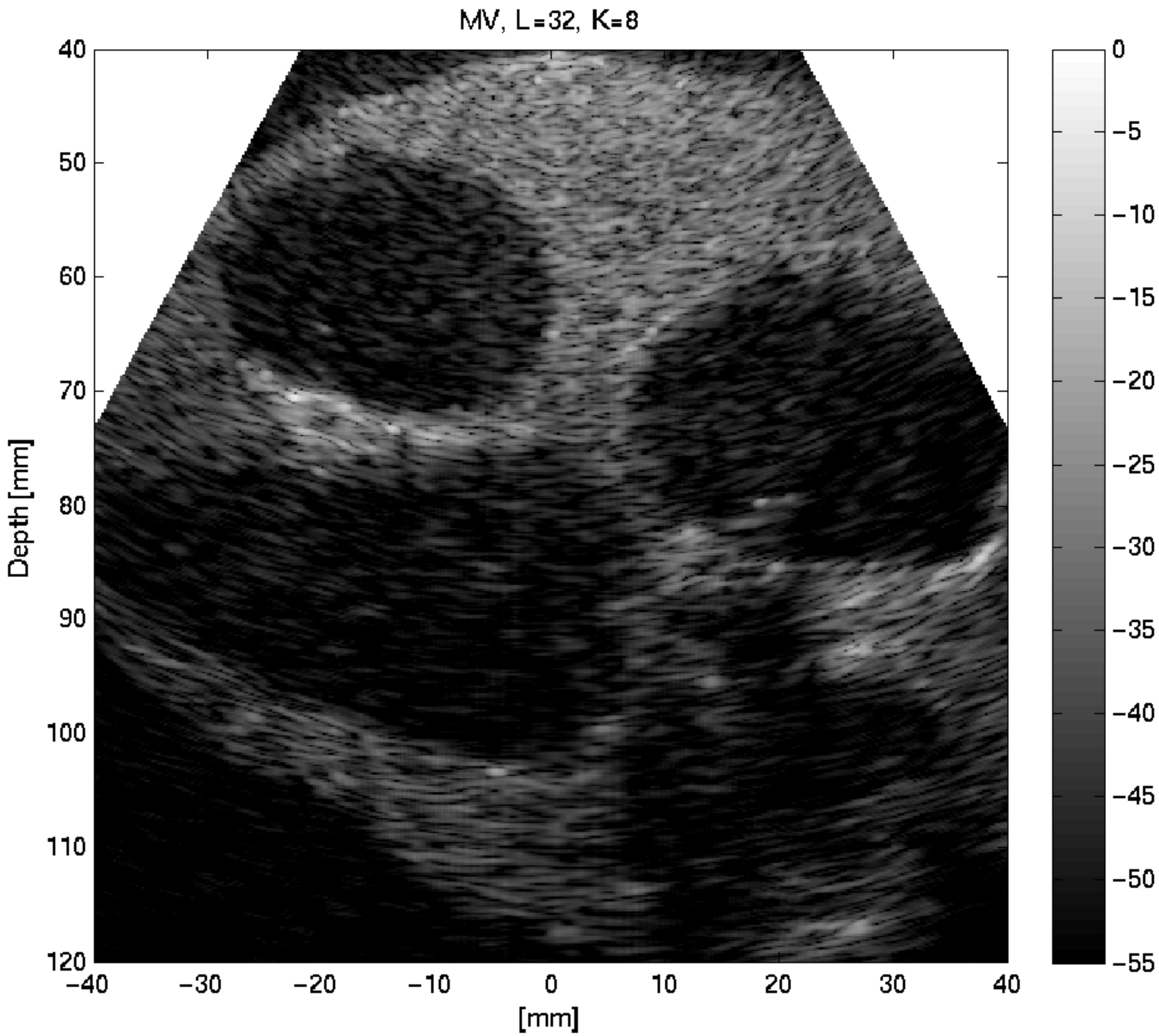


Subarray averaging makes little difference

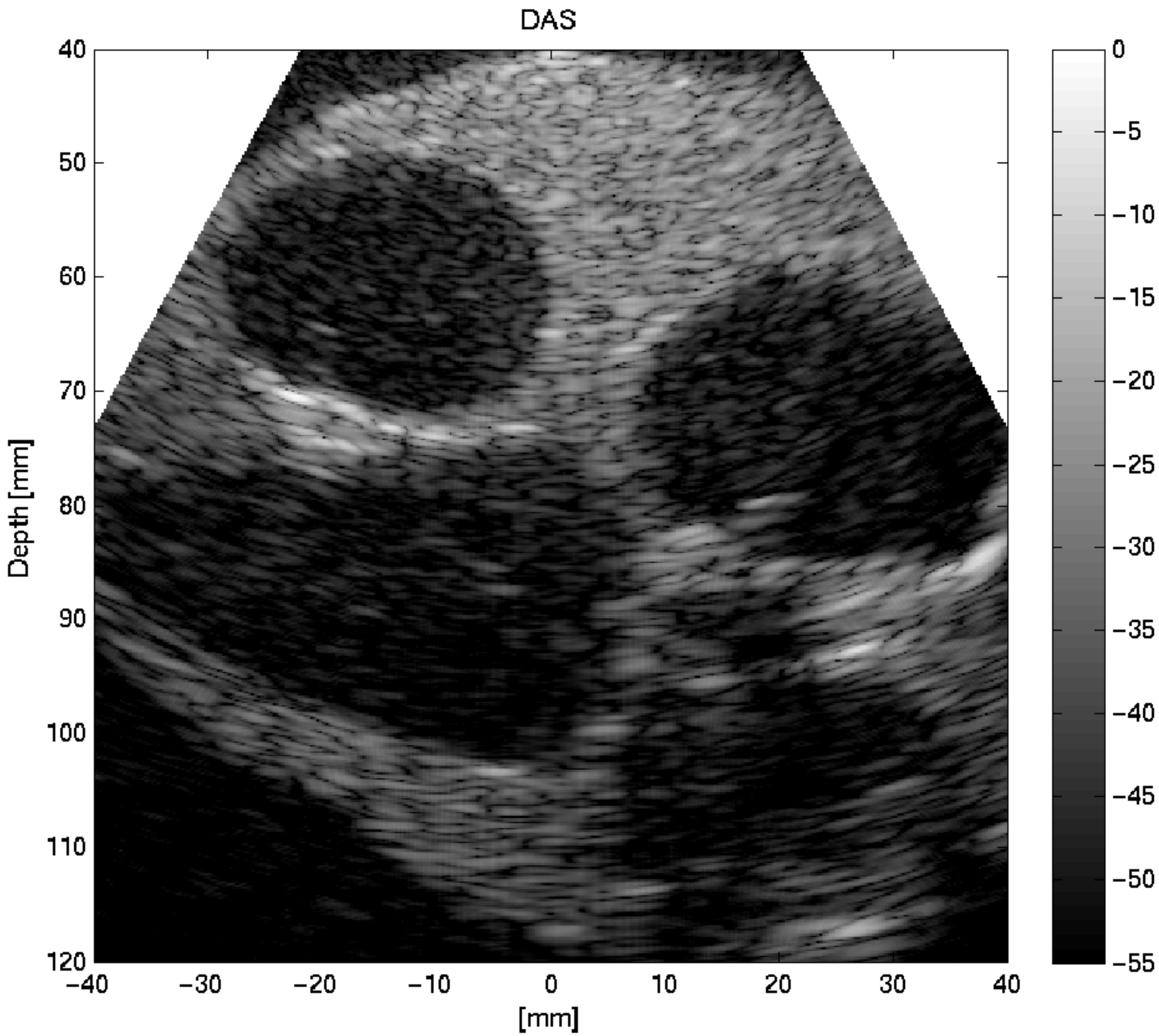

DAS
Depth [mm]
40
50
60
70
80
90
100
110
120
−40
−30
−20
−10
0
10
20
30
40
[mm]
0
−5
−10
−15
−20
−25
−30
−35
−40
−45
−50
−55



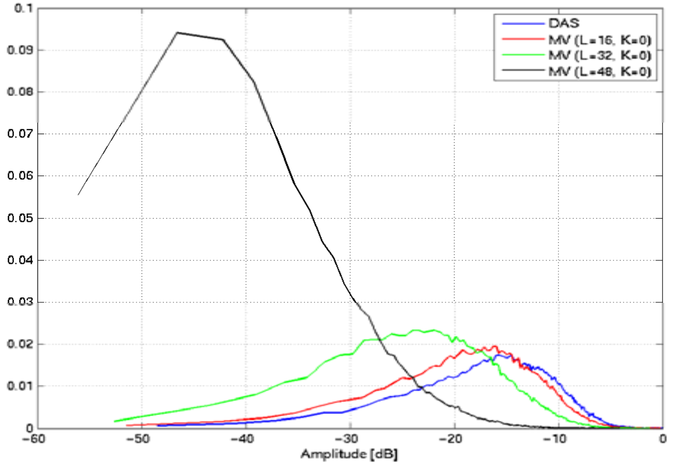
L=32 subaperture, no time averaging, $\delta=1/(10\cdot L)$

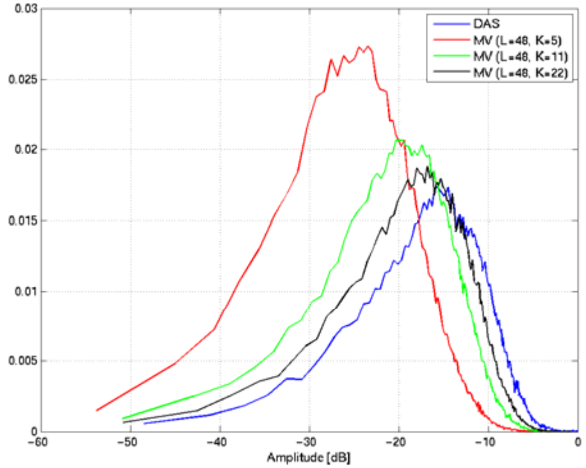


L=32 subaperture, 2K+1=17 time averages, $\delta=1/(10\cdot L)$


DAS
Depth [mm]
40
50
60
70
80
90
100
110
120
−40
−30
−20
−10
0
10
20
30
40
[mm]
0
−5
−10
−15
−20
−25
−30
−35
−40
−45
−50
−55

Distribution of pixel amplitudes





Preferred approach

- Subarray averaging:
  - Ensures a good covariance matrix estimate
  - Is essential to avoid cancellation due to coherence.
- Diagonal loading:
  - For robustness
- Radial averaging
  - Improved speckle
  - Only for covariance estimate, not for beamforming

Related work

- Mann and Walker, Ultrasonics 2002
  - Beamwidth reduction and sidelobe suppression
    - » No subaperture averaging, only single wire target, less coherency problems
  - Improved contrast on cyst phantom
  - Frost beamformer – Capon with FIR
- Sasso and Cohen-Bacrie (Philips), ICASSP 2005
  - Improved contrast on simulated data
  - Subaperture averaging and time averaging over neighbor beams
- Wang, Li, Wu, IEEE Trans. Med., Oct. 2005 & Synnevåg et al, Ultrasonics 2005:
  - Robustness with diagonal loading, tested on array with random element position errors
  - Only tested on single wire target and cysts, not tested handling of coherent targets
- Synnevåg et al, IEEE TUFFC, 2007
  - two very close targets, closer than the limit which can be resolved by DAS. Using this scenario, we have demonstrated that better resolution than DAS was possible even with coherent targets
  - Improved resolution and contrast on wire pairs and heart phantom
- Holfort et al. (IEEE Ultrason. Symp 2007)
  - implicit time averaging since they split the transducers bandwidth into independent bands by FFT, performed independent high resolution beamforming per band, and combined them.
  - Single transmission: very high frame rate
- Synnevåg et al, Ultrasonics 2007:
  - Time averaging over small range gate: better speckle statistics
- Vignon and Burcher (Philips), T. UFFC March 2008
  - First clinical images: in-vivo heart and abdominal images

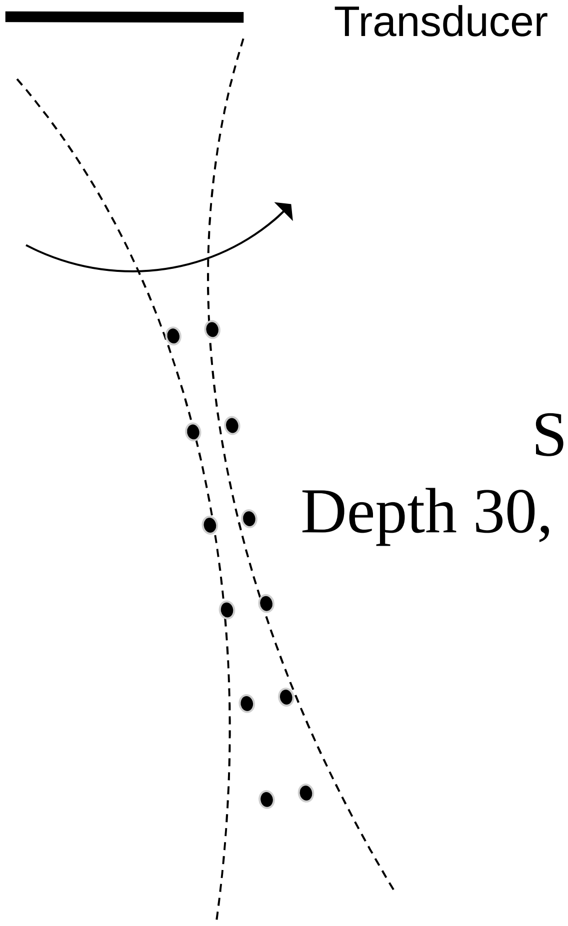
Comments

- Fall-back to delay-and-sum:
  - Subaperture averaging as the subaperture size -> 1:
    - » = delay-and-sum beamforming
  - Diagonal loading as the diagonal term becomes dominant:
    - » = delay-and-sum beamforming
- Variation of a single parameter allows one to adjust the method so that it falls back to conventional delay-and-sum beamforming.
- Challenge:
  - How to do subaperture averaging on a curved transducer? (curved array or sonar array)

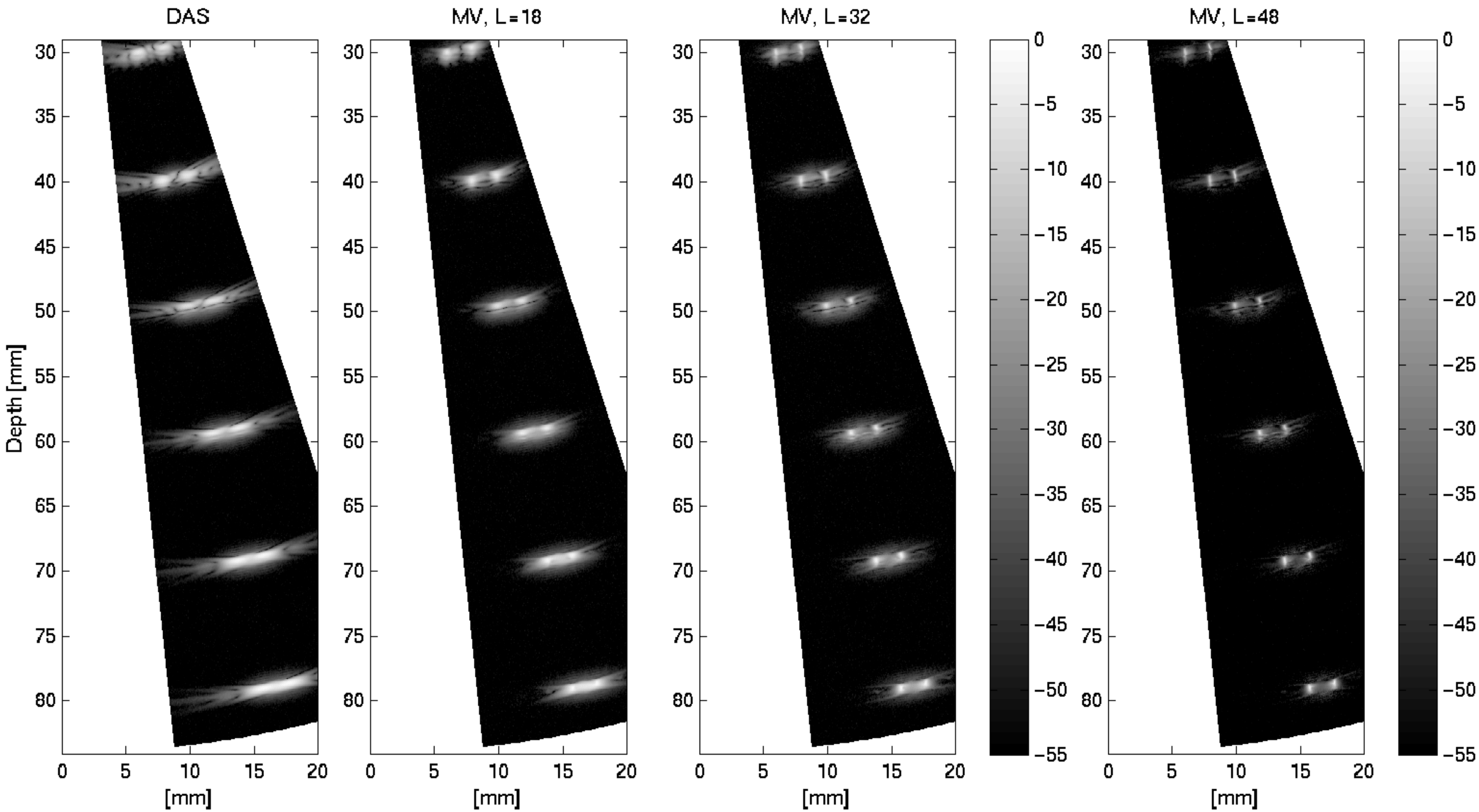
Results: simulated data

- Field II
- 96 element, 4 MHz transducer
- All transmitter / receiver combinations
- Applied full dynamic focus
- White gaussian noise added

Simulated data-set



Spacing 2 mm
Depth 30, 40, 50, 60, 70, 80 mm

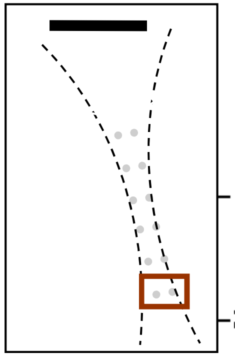

DAS
MV, L=18
MV, L=32
MV, L=48
Depth [mm]
[mm]
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
-55

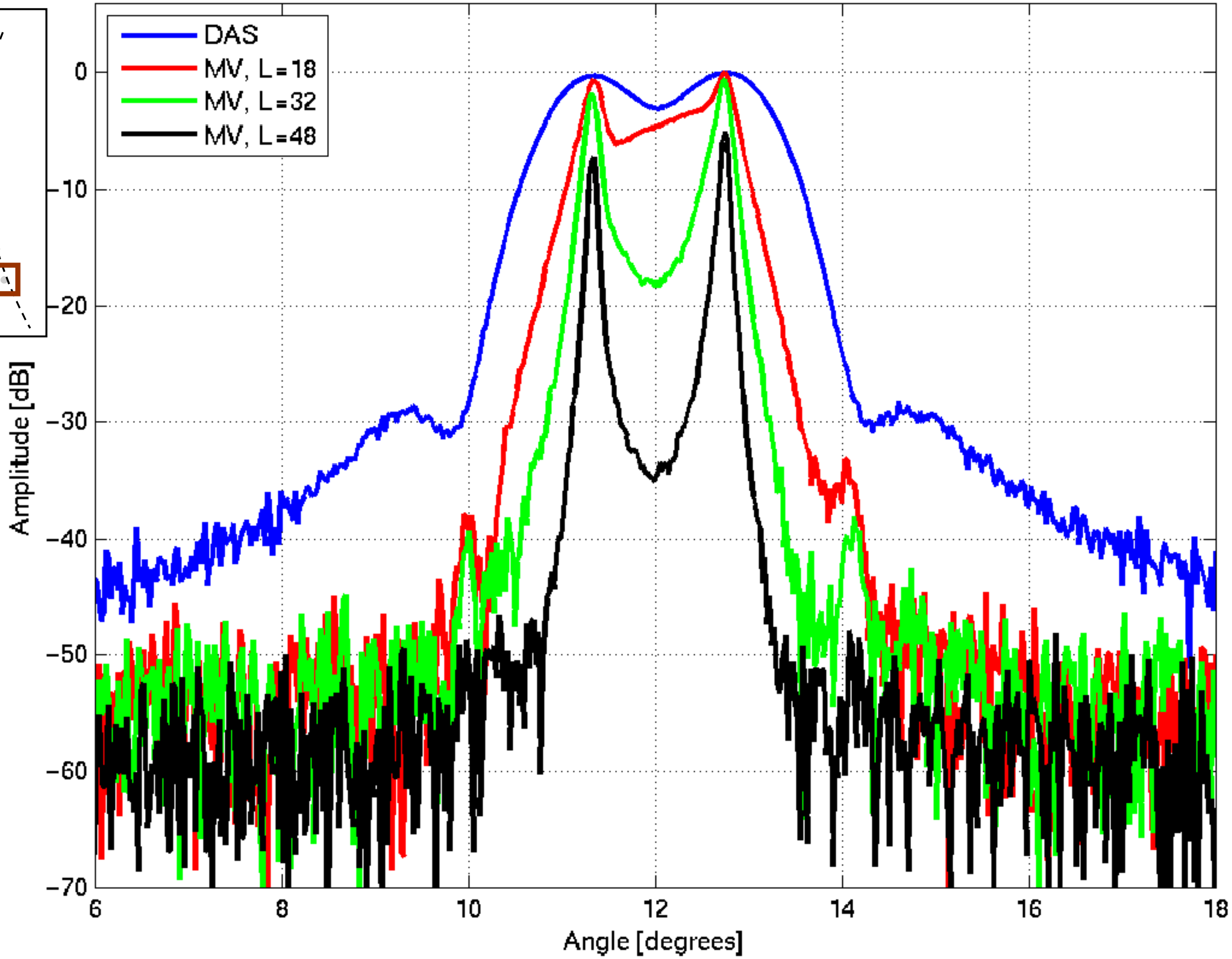
Parameters

- Aperture: M=96
- Subapertures that overlap with L-1 elements
  - L=48, 96-48+1 = 49 averages
  - L=32, 96-32+1 = 65 averages
  - L=18, 96-18+1 = 79 averages
- Small amount of diagonal loading
  - R is replaced by $R + \delta \cdot tr\{R\} \cdot I$
  - Ensures good conditioning of R
  - Default: $\delta=1/(100 \cdot L)$ where diagonal term is $\varepsilon = \delta \cdot tr\{R\}$
  - [Have also used up to $\delta=1/L$ ⇔ i.e. same variance for R and the added white noise]

UNIVERSITY

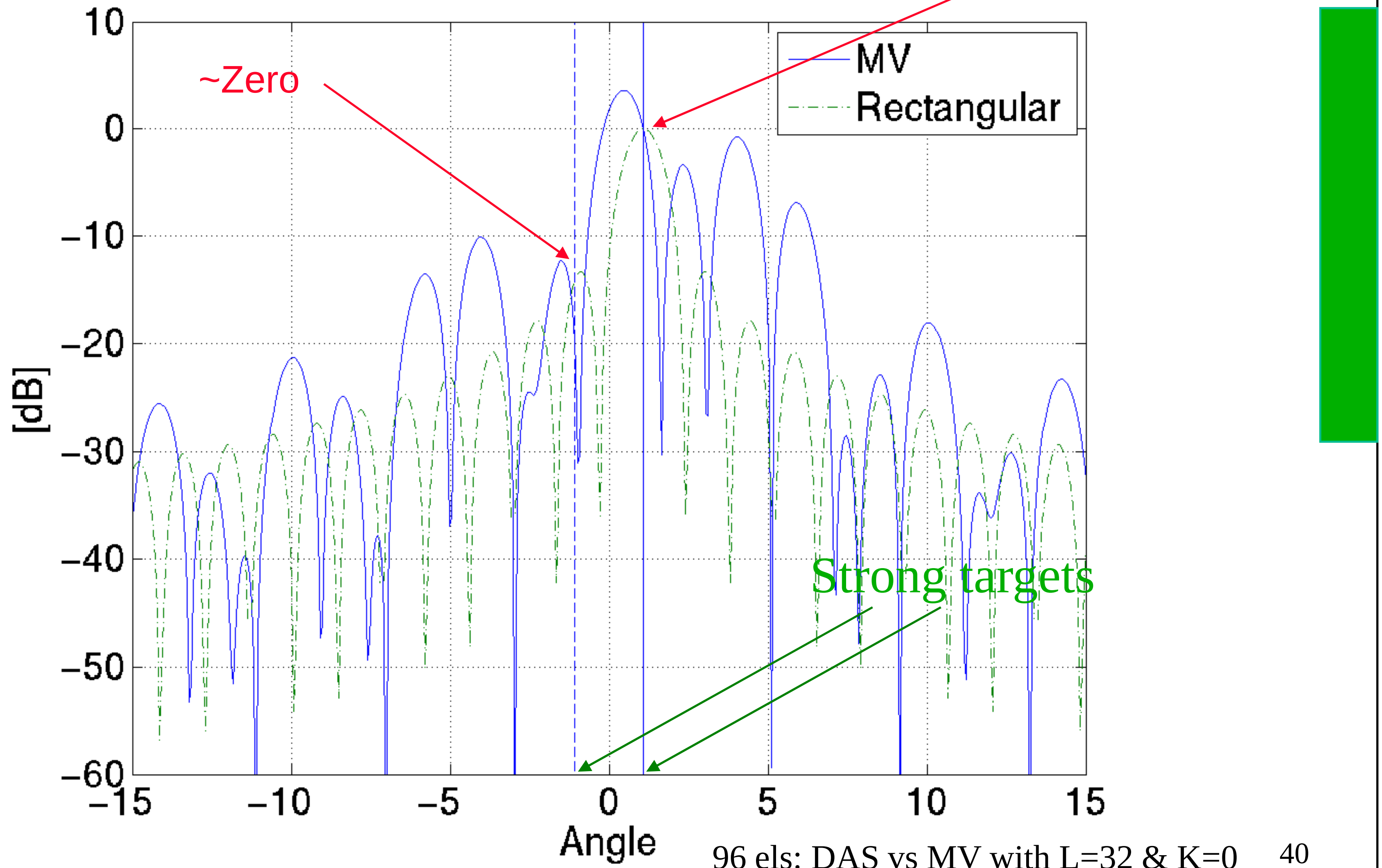
80 mm depth





UNIVERSITY OF OSLO

Examples of beampatterns (two wire targets, 80 mm)



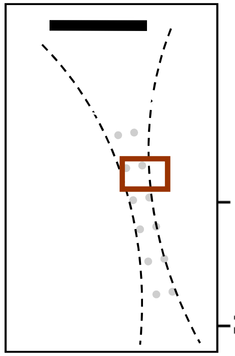
96 els: DAS vs MV with L=32 & K=0

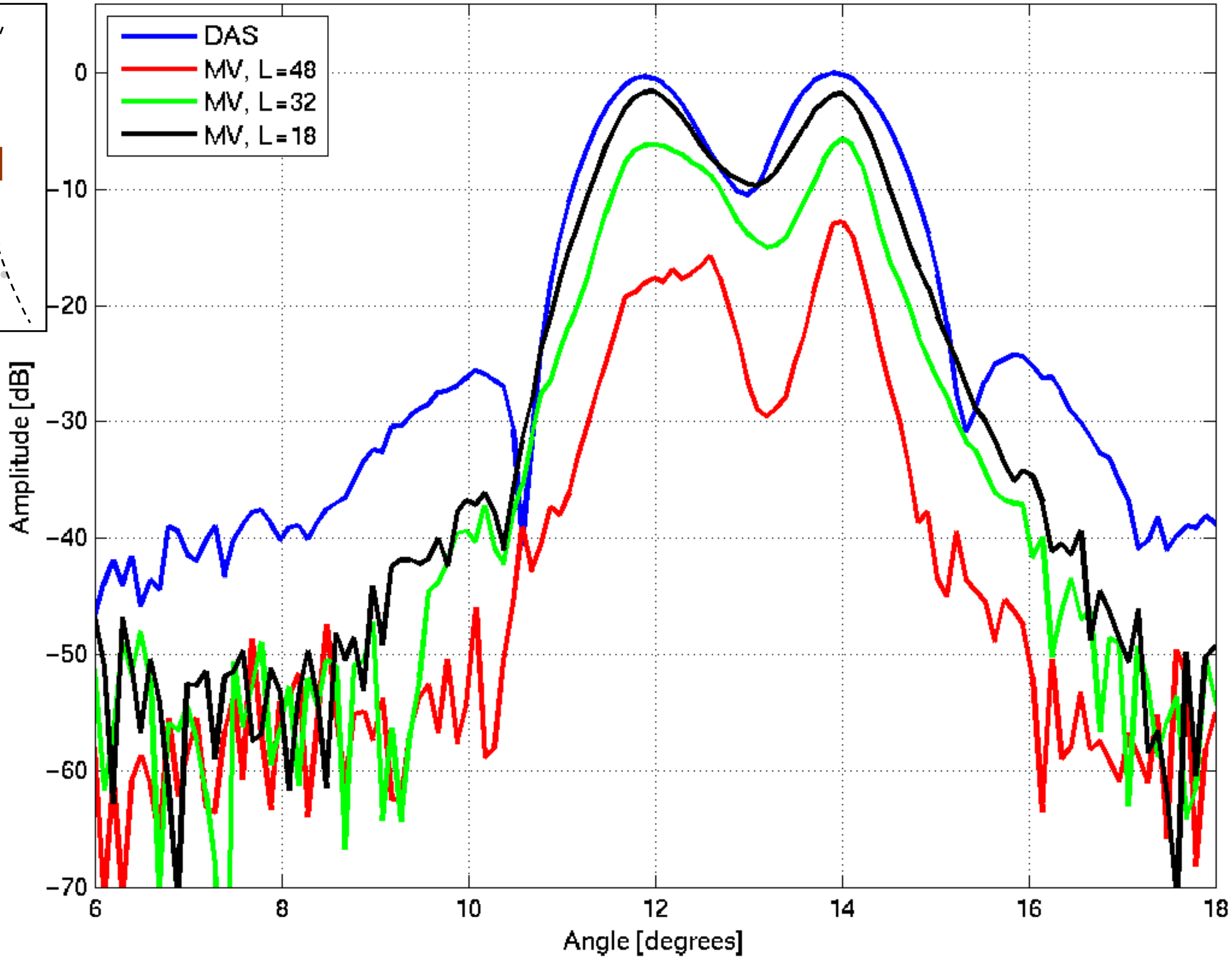
Robust adaptive beamforming

- Processed the data with 5% error in acoustic velocity
- Applied regularization:
  - Replaced **R** with **R** + ε**I**
  - Large ε => delay-and-sum

UNIVERSITY OF OSLO

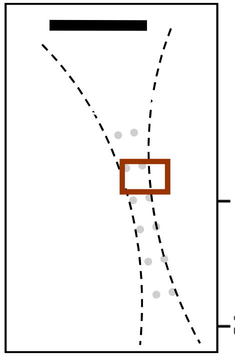
5 % error in c: Sensitivity to subarray size

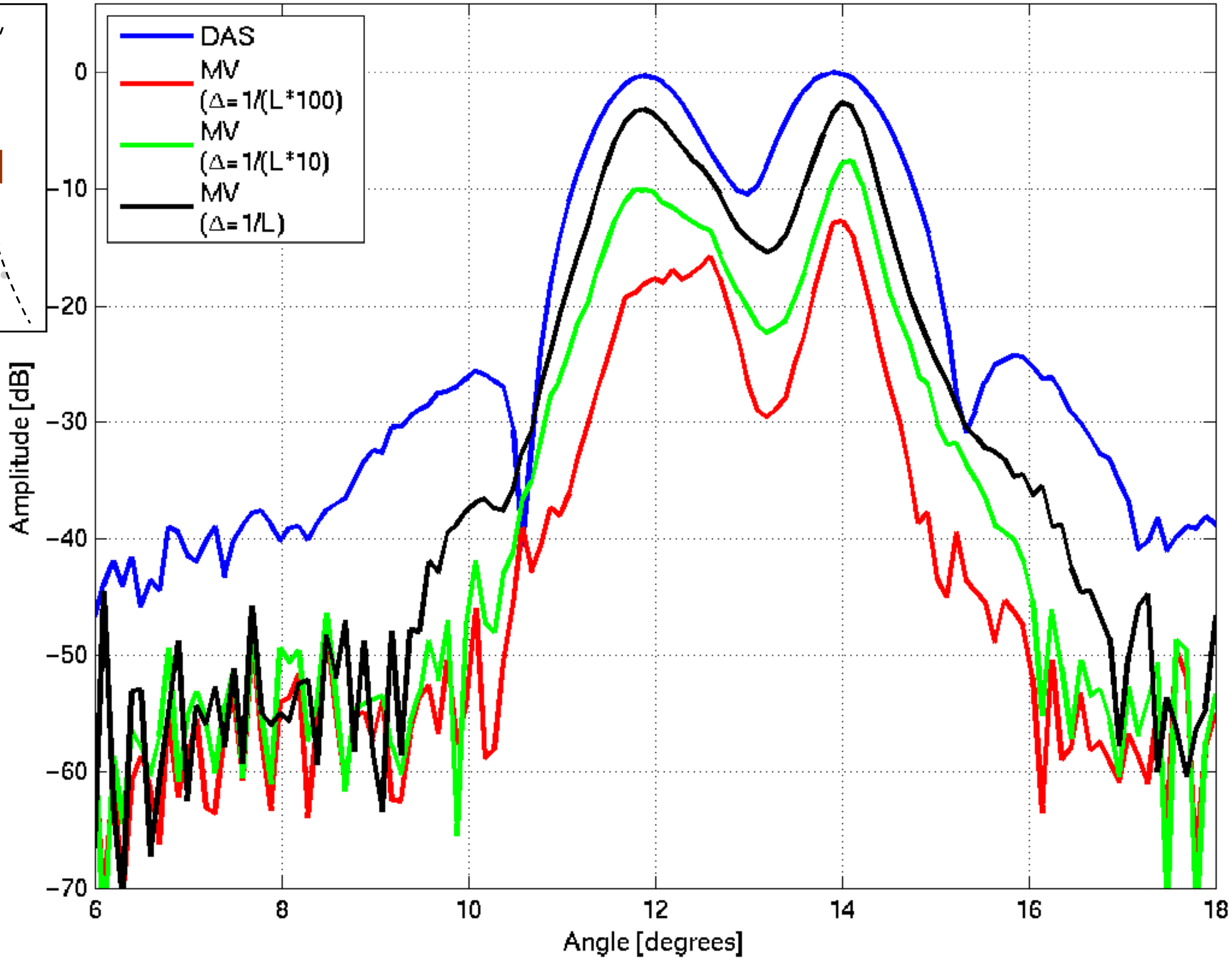




UNIVERSITY OF OSLO

5 % error in c (L=48) Sensitivity to diagonal term



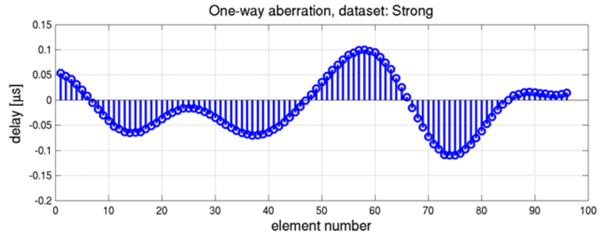


Phase aberrations

- Point target at 70 mm, 2.5 MHz 64 element phased array
- 1D aberrations: time-delays as if the aberrator was on the transducer surface.
- Unweighted delay-and-sum (DAS) beamformer and a MV beamformer.
  - A. Austeng, T. Bjåstad, J.-F. Synnevaag, S.-E. Masøy, H. Torp and S. Holm "Sensitivity of Minimum Variance Beamforming to Tissue Aberrations", IEEE Ultrasonics Symposium, Nov. 2008.

Aberrator

- Correlation length: 2.46 mm
- Delay
  - » Weak (imaging through thorax): 21 ns rms/90 ns peak
  - » Intermediate (abdominal imaging): 35 ns rms/150 ns peak
  - » Strong (abdominal imaging): 49 ns rms/210 ns peak
  - » Very strong (breast imaging): 68 ns rms/290 ns peak



Results, phase abberation

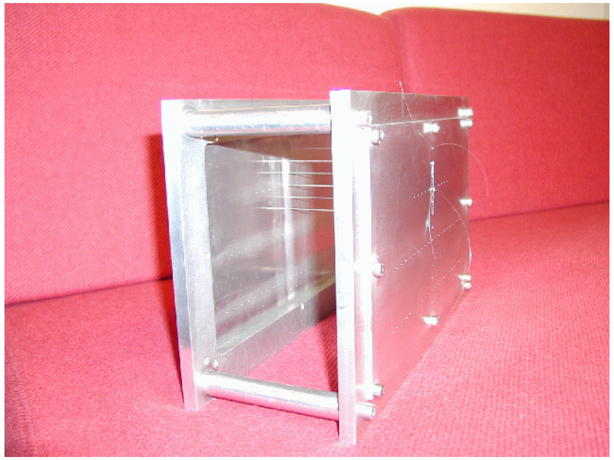
- Main lobe of the MV beamformer was narrower or approximately equal to that of DAS
  - -6 dB lateral beamwidth being 40%, 67%, 83%, and 106% of DAS for the four cases.
- The aberrations affected the sidelobe structure producing non-symmetric patterns, but with comparable values for the maximum sidelobe levels.
  - For the weak aberrator, the MV beamformer performed better (1-5 dB) than the DAS beamformer.
- A slight reduction in sensitivity.
  - Very strong aberration: the main lobe value was decreased by 1.4 dB compared to the DAS beamformer.
  - For the other scenarios: the decrease was 0.9, 0.6, and 0.4 dB.

Phase aberrations and MV

- MV – balancing of performance and robustness.
  - Spatial smoothing, diagonal loading, time averaging over about a pulse length
- MV: substantial decrease in main lobe width without increase in sidelobe level in aberrating environments.
  - It does not degrade the beam even with very strong aberrators.
  - MV can handle realistic aberrations with a performance which is better than or equal to that of DAS.

Experimental data

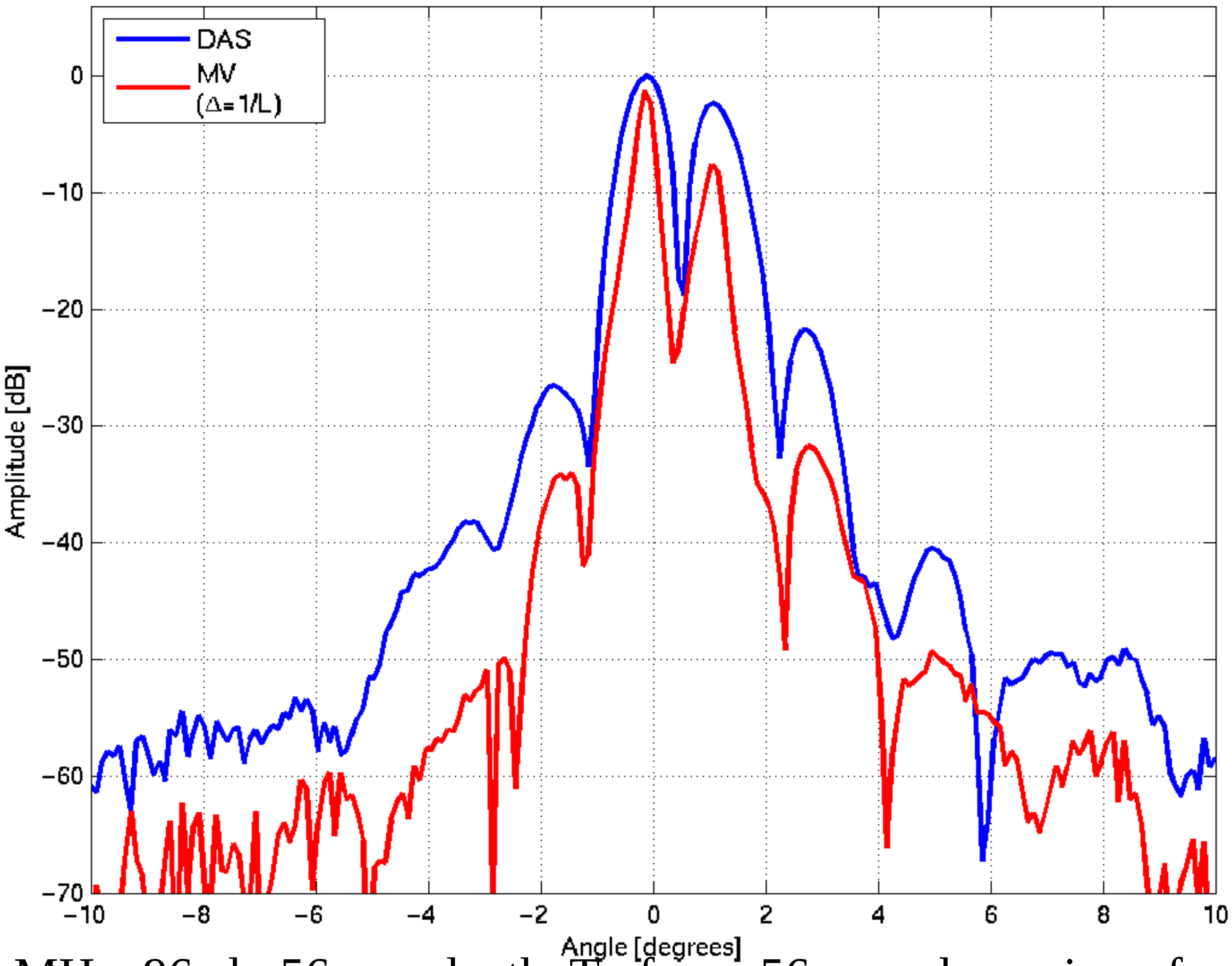
- Specially programmed GE Vingmed ultrasound scanner
  - » 96 element, 3.5 MHz transducer @ 4 MHz
  - » Specially made wire target, spacing 2 mm



- Biomedical Ultrasound Laboratory, University of Michigan
  - » 64 element, 3.5 MHz transducer
  - » heart-phantom

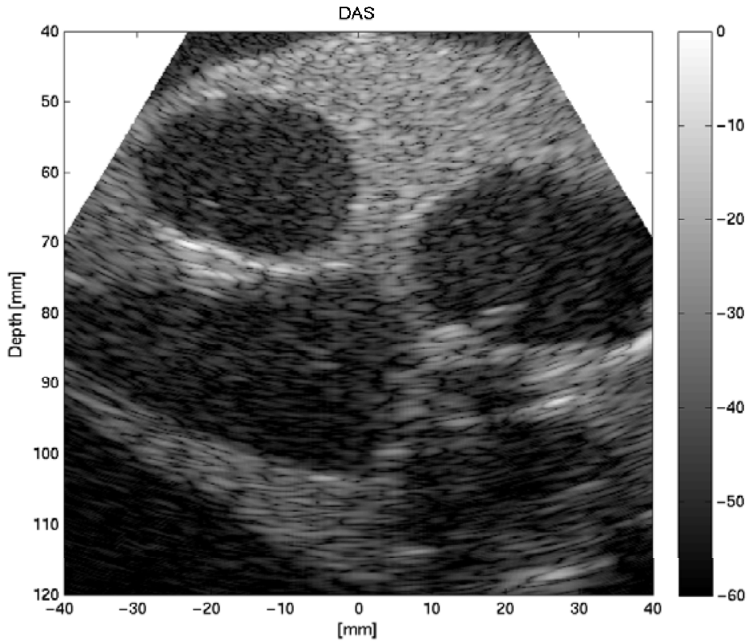
UNIVERSITY
OF OSLO

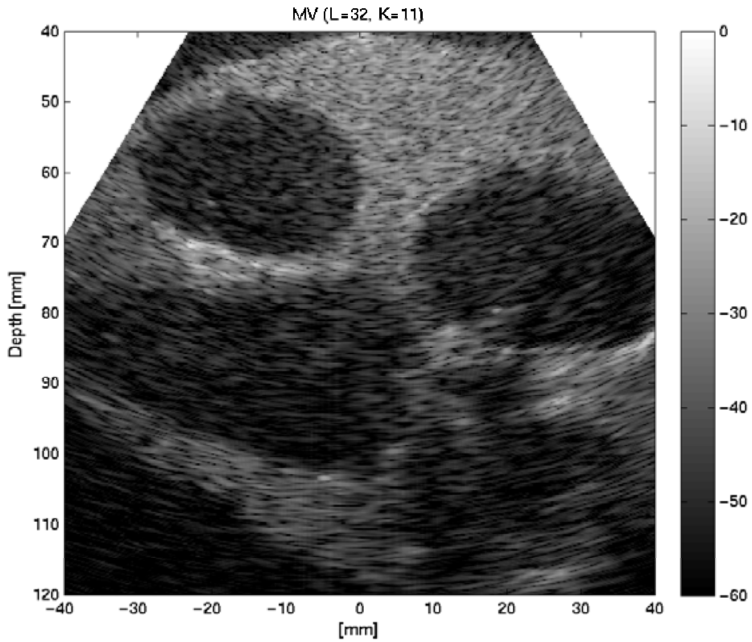
Point targets: GEVU scanner



4 MHz, 96 el., 56 mm depth. Tx focus 56 mm, dynamic rx focus

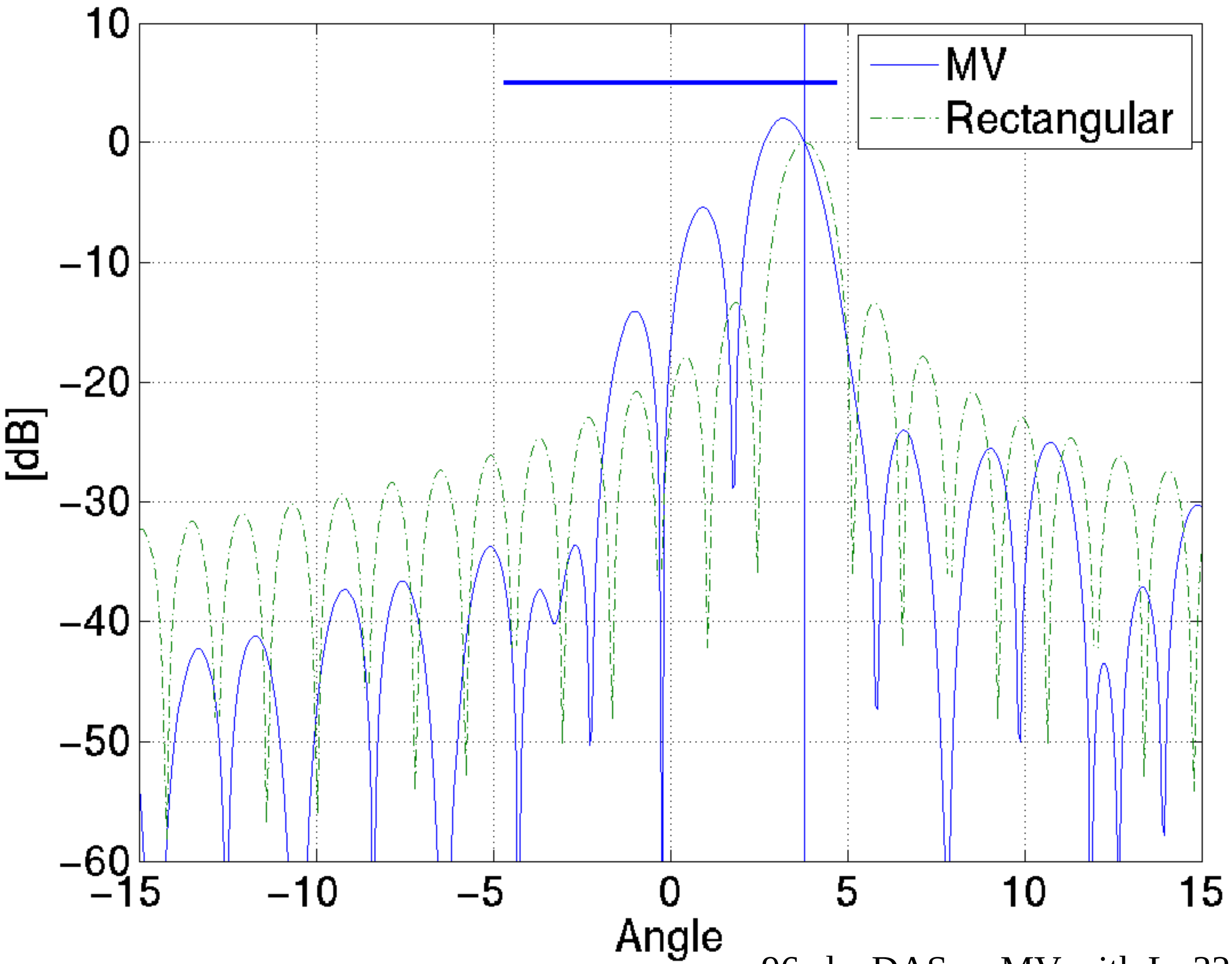
Heart phantom





UNIVERSITY
OF OSLO

Beampatterns (cyst)



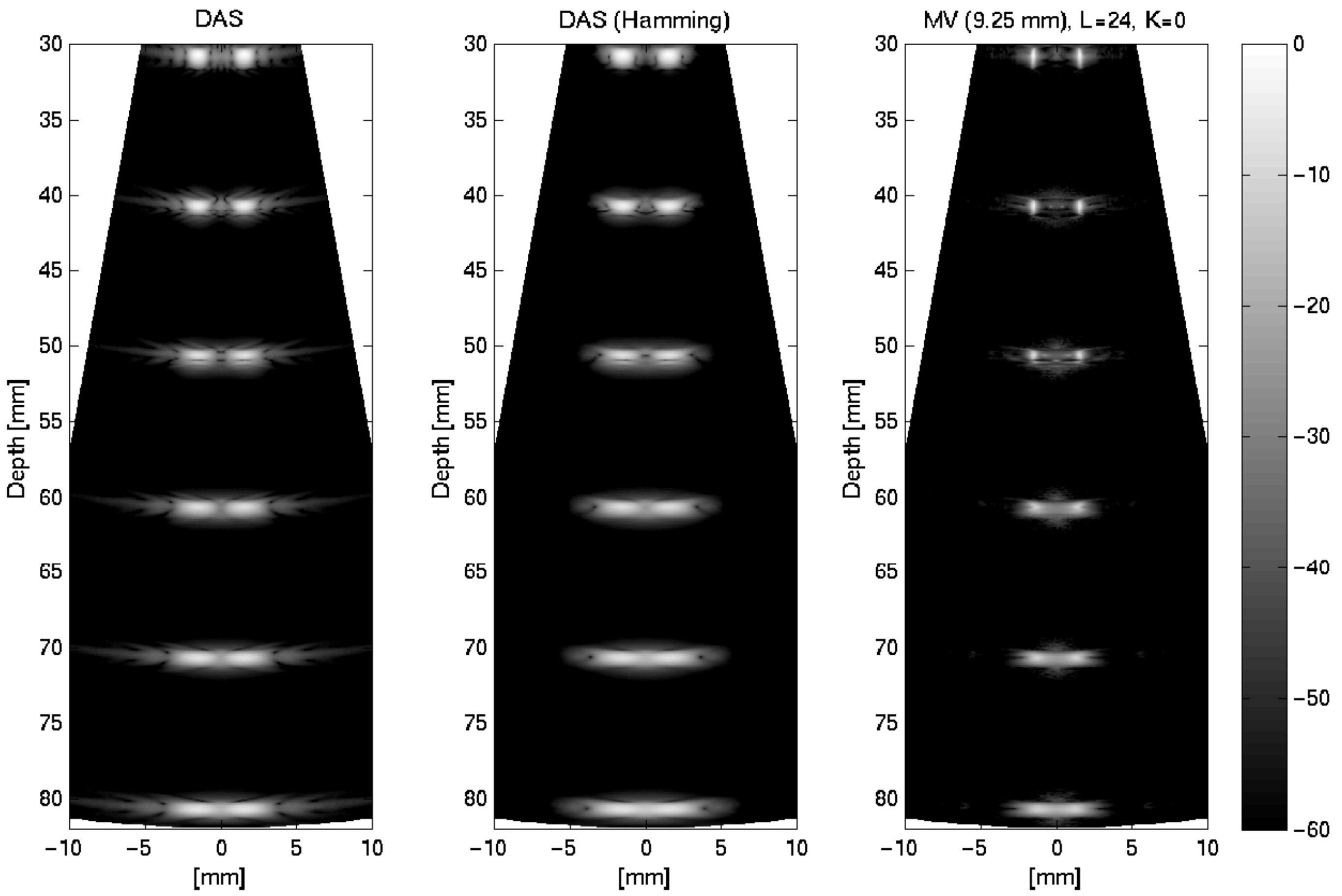
96 els: DAS vs MV with L=32 & K=0

Other benefits than resolution

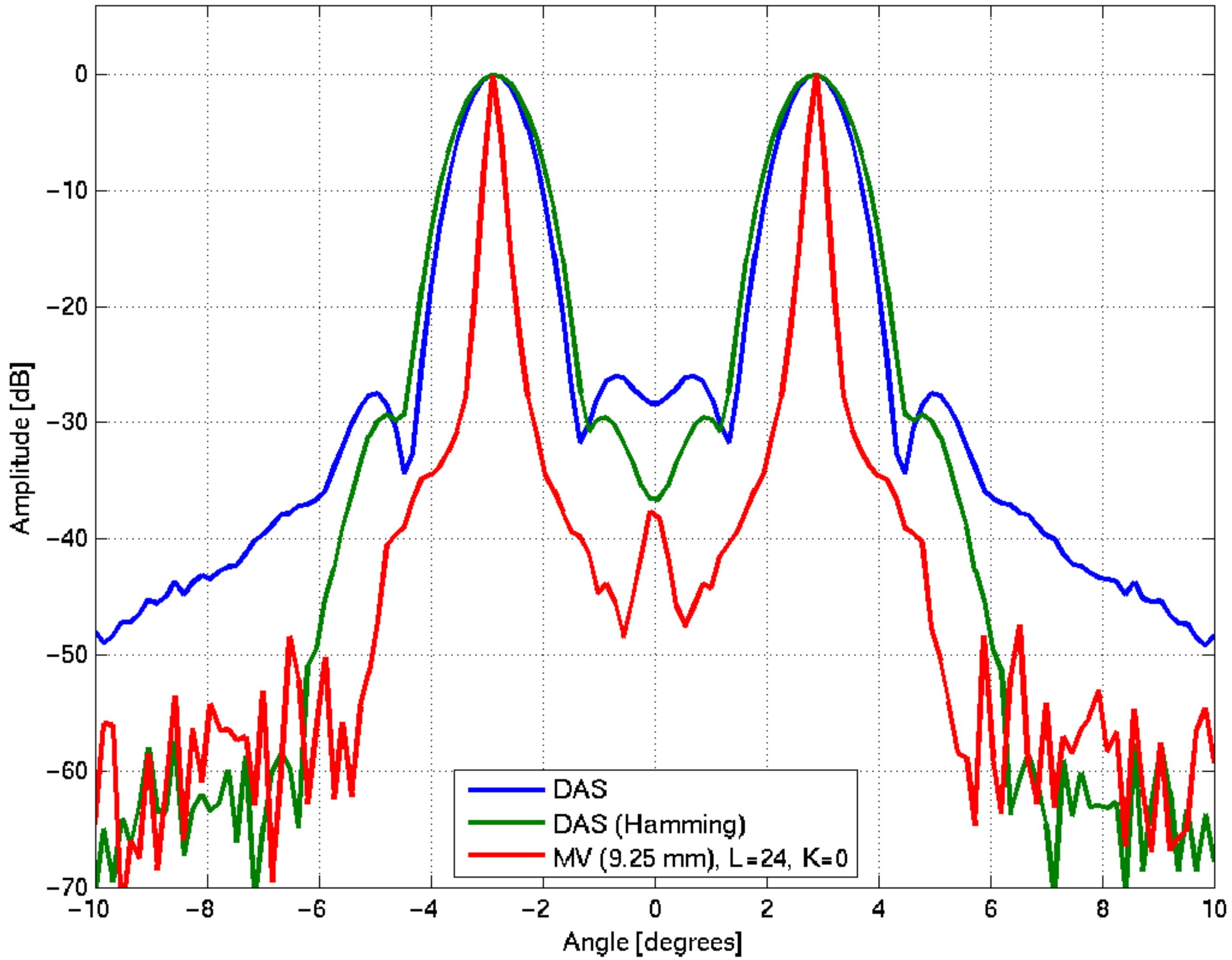
- Reduced transducer size
  - 18.5 mm transducer (DAS) vs 9.25 mm transducer (MV)
- Parallel receive beamforming
  - 32 Tx/rx lines (DAS) vs. 8 Tx lines (MV with 4 parallel beams)
- Increased penetration depth
  - 3.5 MHz transmission (DAS) vs. 2 MHz transmission (MV)
- Synnevåg et al ”Benefits of High-Resolution Beamforming in Medical Ultrasound Imaging”, IEEE UFFC, Sept. 2009.

UNIVERSITY
OF OSLO

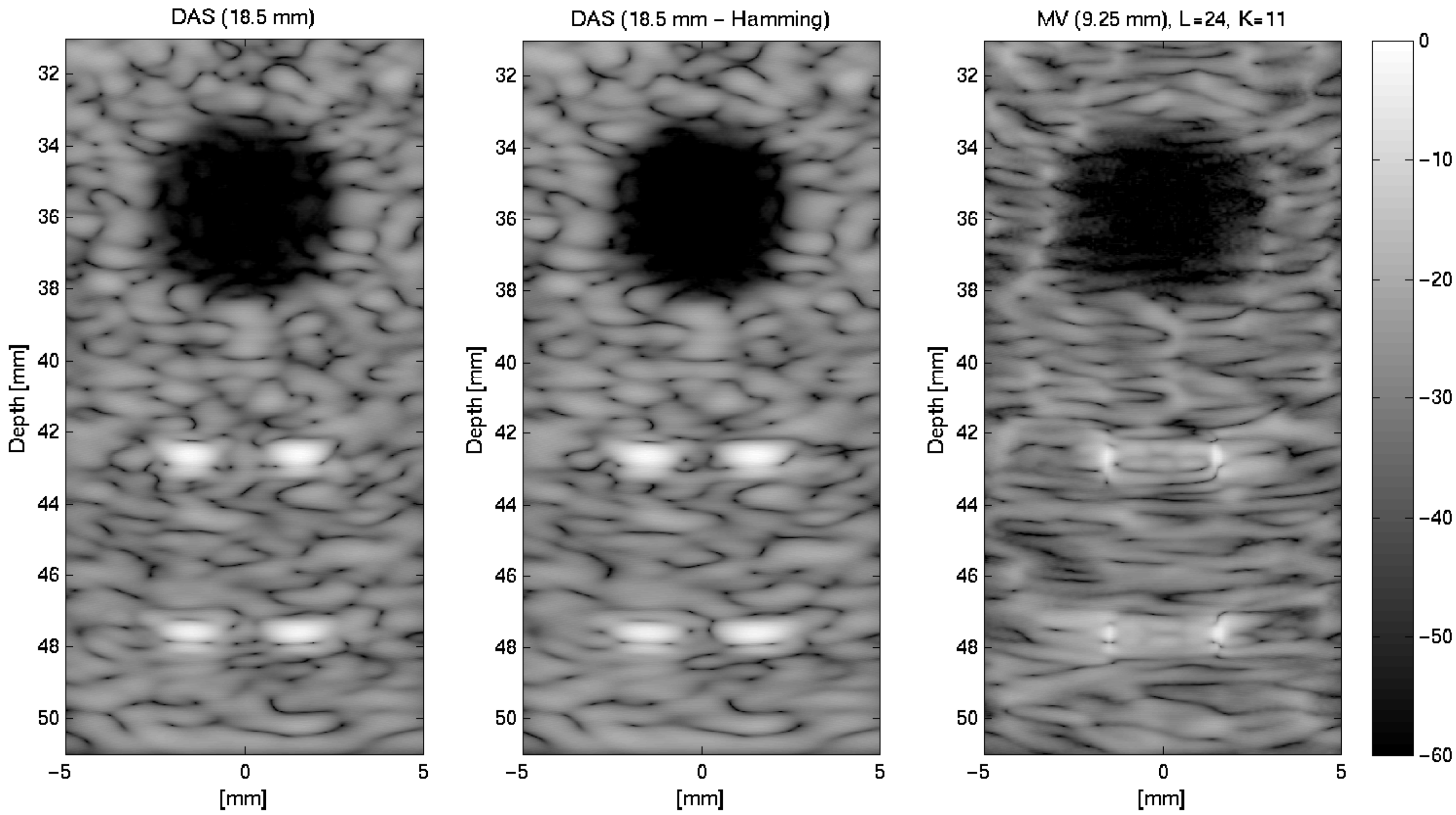
Half the transducer size



Half the transducer size (2)

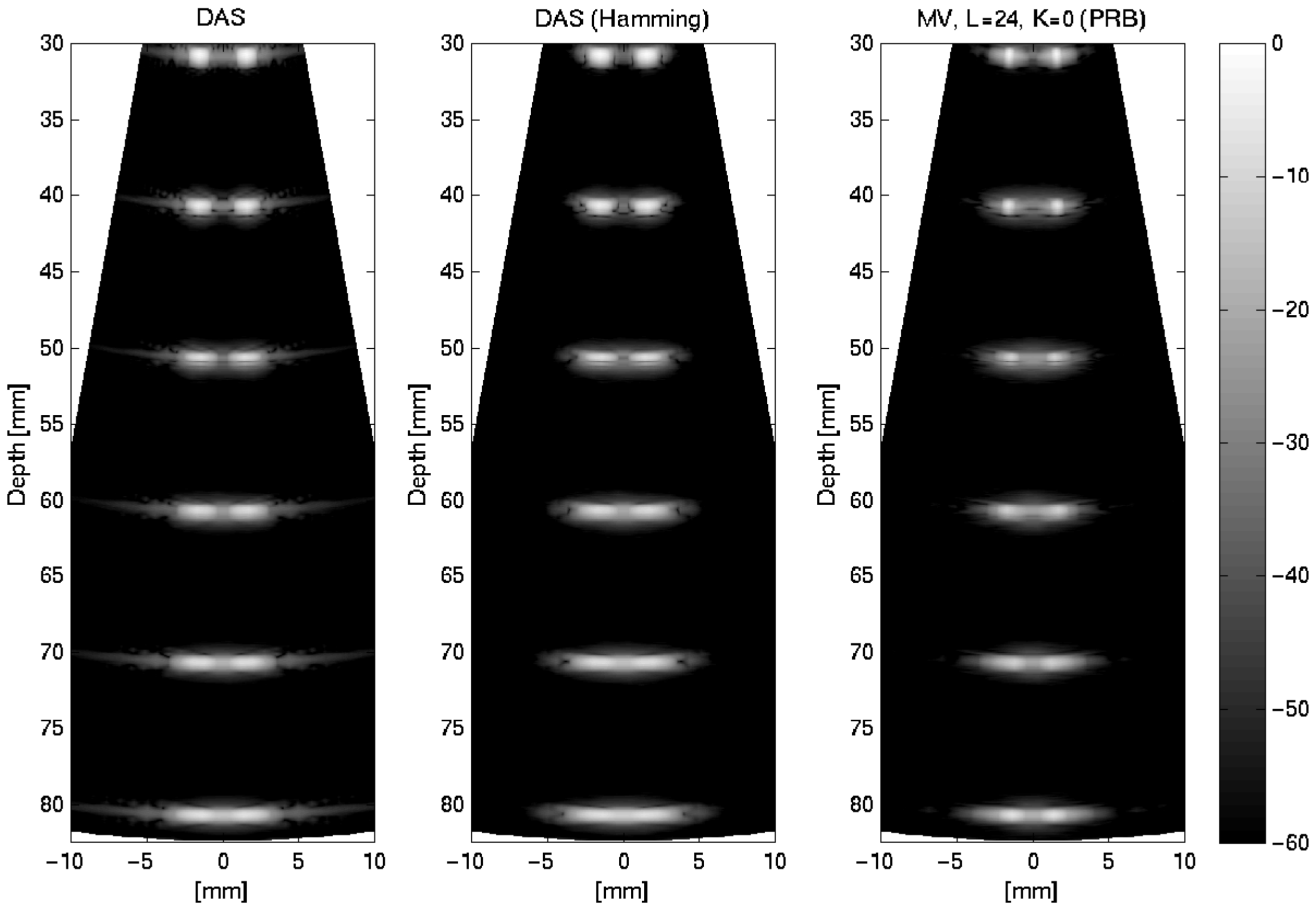


Half the transducer size (3)

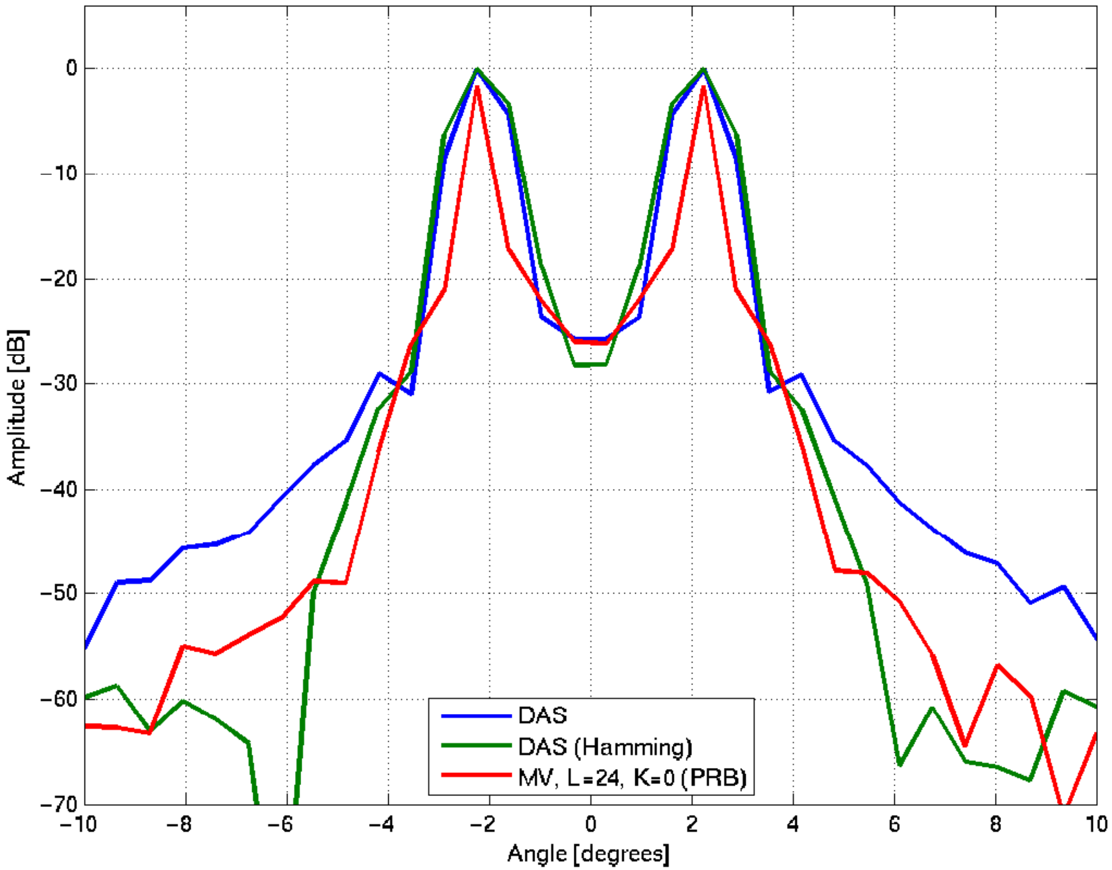


UNIVERSITY
OF OSLO

4 times wider transmit beam & parallel receive beams = 4 times the frame rate

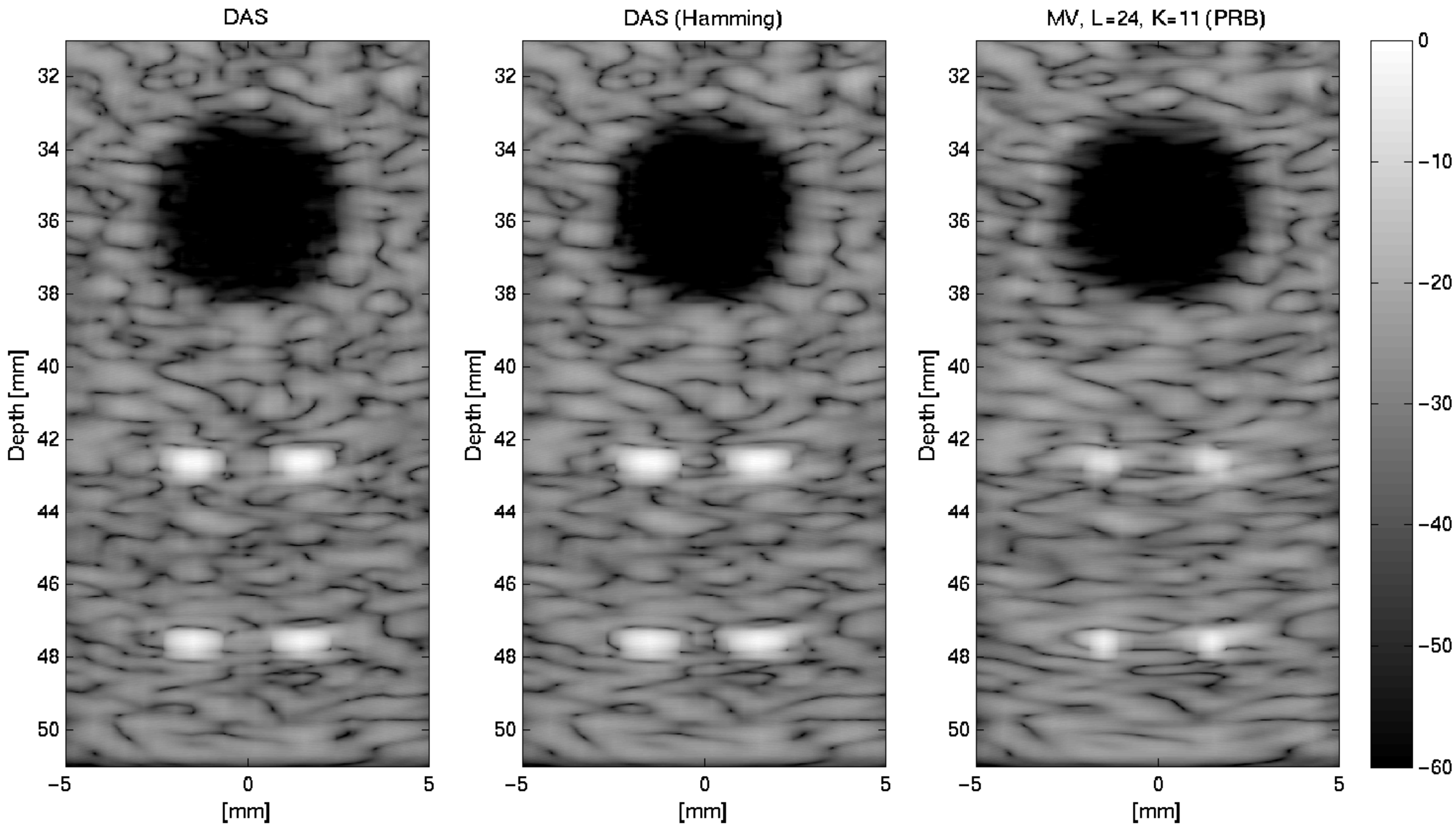


Parallel receive beams (2)



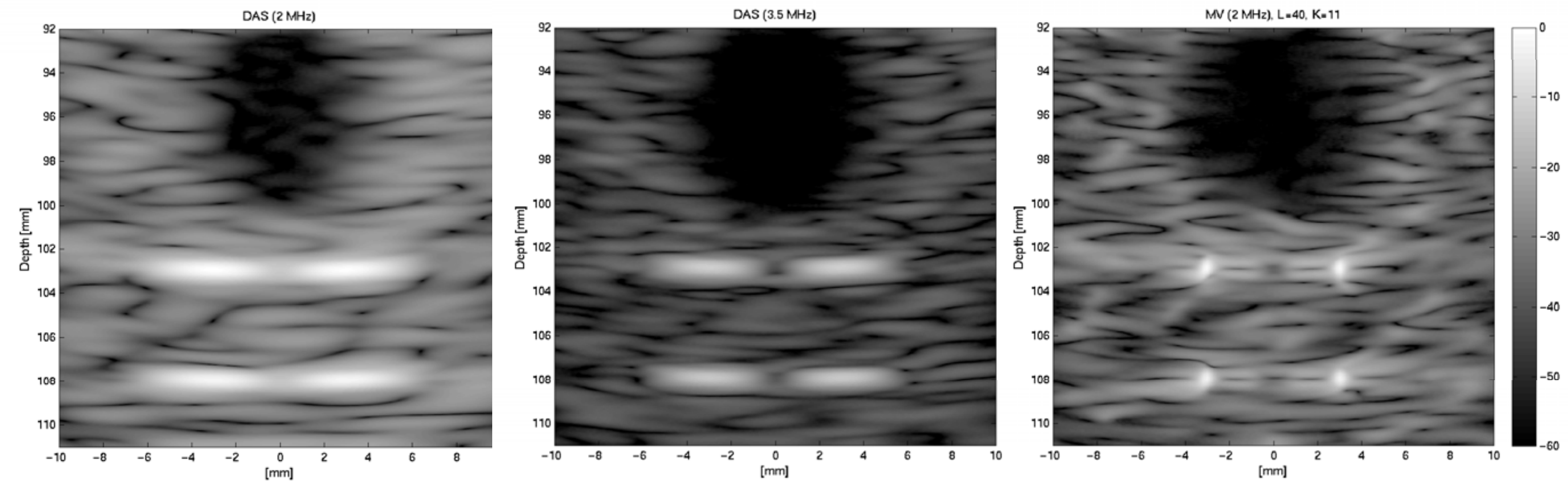
UNIVERSITY OF OSLO

Parallel receive beams (3)



2 MHz vs. 3 MHz transmission

DAS 2 MHz DAS 3.5 MHz MV 2 MHz



Computational cost

- M elements, L-size subarrays
- Delay is the same as for delay-and-sum
- Matrix inversion $2L^3/3$ or $O(L^3)$ + estimation of weights
  - Saves computations by using smaller subarrays, L, instead of more diagonal loading
- Application of weights (= DAS): O(M)

Simplified Capon

- Select the window with smallest output among P=4-12 pre-defined windows rather than estimate window from data
  - No matrix inversion $2L^3/3$, only P x DAS: $2P \cdot M$
    - » Ex: M=96, L=32 => $2L^3/3 \approx 22000$ vs P=10: $2P \cdot M \approx 2000$
  - More robust than Capon: no possibility for signal cancellation if windows have been chosen properly
- J.-F. Synnevåg, A. Austeng, and S. Holm, A Low Complexity Data-Dependent Beamformer, IEEE UFFC, Feb 2011.

Conclusion

- Applied MV beamformer to medical ultrasound imaging
- Balancing of performance and robustness.
  - Spatial smoothing which is important for dealing with multiple reflectors
  - Diagonal loading which helps make the method robust
  - Time averaging over about a pulse length in estimating the covariance matrix. The latter ensures that the speckle resembles that of DAS.
- Shown improvement in image quality of realistic images
- Demonstrated 3 examples where MV may be benefitial
  - Smaller aperture, higher framerate, lower frequency
- Several methods for reducing computational cost
- Needs more testing on relevant image data